THE INTERACTION OF PURE SCIENTIFIC RESEARCH AND ELECTRICAL ENGINEERING PRACTICE

A view of the front of the Research Laboratories of The General Electric Company, Ltd., at Wembley, England. These laboratories cover approximately an area of 90,000 square feet, and the research staff numbers about 200 persons occupied entirely in research work in connection with various problems in electrotechnology.

THE INTERACTION OF PURE SCIENTIFIC RESEARCH AND ELECTRICAL ENGINEERING PRACTICE

A COURSE OF ADVANCED LECTURES DELIVERED BEFORE THE UNIVERSITY OF LONDON, OCTOBER AND NOVEMBER, 1926

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PREFACE

As the objects and scope of this book are explained in the Introduction, it is only necessary here to record the Author's obligations to those Firms and gentlemen who have kindly assisted by furnishing diagrams and illustrations. To the General Electric Company, Ltd., of London, and to Mr. C. C. Paterson, the Author is indebted for information and for photographs of the General Electric Company Research Laboratory at Wembley. Also to Messrs. Isenthal & Co., Ltd., for diagrams and illustrations in Chapter VI. To Mr. W. M. Mordey, and the Royal Institution of Great Britain, for the illustrations in Chapter II. connected with his experiments on hysteretic repulsion. Also to the Institution of Electrical Engineers for some blocks in Chapter V.; and to Mr. Kilburn Scott for permission to use some blocks in a paper by him on piezo-electricity. The Author desires to record his thanks to the General Electric Company, Ltd., of London, and to Messrs. Isenthal & Co., Ltd., for the loan of apparatus and slides illustrating the lectures themselves.

J. A. F.

University College,
London, July, 1927.

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SCIENTIFIC RESEARCH AND ELECTRICAL ENGINEERING

INTRODUCTION

THE Work of the Electrical Engineer is mainly concerned with devices for making the world smaller by the annihilation of space and time, and also with means for transferring energy from one locality to another or utilising forms of Power which would otherwise run to waste. The steady increase in the population of the world and its tendency to concentrate into great cities renders it necessary to have appliances for rapid transport whereby materials and persons can be quickly moved between the outskirts and the centres of cities, or from town to town. This necessitates tapping new sources of Energy and its distribution as required.

Furthermore, humanity is characterised by continually progressive desire. We ask for more and better Illumination than that which contented our forefathers. We require more speedy Transit, less manual labour, greater supplies of Power for manufacture, more News of the world and Intercourse with each other. The latest demand, which is satisfied by Broadcasting, is for the continual distribution of music and speech over large areas which can be heard in our own homes without fatigue or exposure to the weather or long journeys.

All these things are given to the world by the Electrical Engineer. Politicians and Legislators are apt to imagine that their own work is of great importance. In truth we could with advantage dispense with much of it. But we could not dispense with the labours of the Electrical

Engineer, because it is he who meets those imperative needs which the continual pressure of population on the means of subsistence brings into existence. If there is any doubt on this point we have only to imagine the state to which we should be reduced if that nimble servant of humanity, called an electric current, were by some freak of Nature withdrawn from our service to-morrow. With that would disappear in the twinkling of an eye much that now makes for the comfort and convenience of life. Telegraphs, Telephones, Electric Bells and Railway Signalling, which alone renders express steam locomotion possible, would vanish. Candles, Paraffin Oil, and Gas, would again have to take the place of electric lighting. Numerous factories would be rendered useless and all electric street cars and railways put out of operation. Great electric industries, such as the preparation of graphite, carborundum, calcium carbide, cyanamide, fixation of nitrogen for fertilisers, production of aluminium, magnesium, calcium, sodium, copper, ferro-alloys, and alloy steels, such as the invaluable vanadium steel, would cease. Enormous multitudes of workers would be thrown out of employment All the pleasures of motoring, broadcasting, moving pictures, and many domestic conveniences would be known no more. In many respects we should be plunged back again into the restrictions and privations of long by-gone days.

No general strike on the largest scale could inflict a tithe of the injury on our modern life which would be experienced if the work of the electrical engineer in the last half century were to be thus annihilated. It has been his achievement to compel this wonder-working current to perform these daily marvels in the service of men, and much of that which alone renders life tolerable under modern conditions is entirely his work.

But the edifice of invention which the electrical engineer has built up is erected on a foundation of pure scientific research. The engineer has utilised that which the scientific investigator has found, and without the materials

gathered by the disinterested labours of pure scientific workers there could have been no applications in common life.

The object of the present book is, then, to expound in some detail the above statements.

In the spring of 1926 the University of London invited the writer to give a Course of eight public lectures on this subject. They were given at the Institution of Electrical Engineers in October and November of that year. At the request of many who heard those lectures and thought they might appeal to others not present if put into print, the Author has endeavoured to give the substance of those lectures with some amplifications in the present volume.

The subject is of extreme importance from a public point of view. The serious lessons impressed upon us by the great European War of 1914–18 have made us better acquainted with the urgent necessity of cultivating and fostering scientific research We have seen that even from the point of view of national safety it constitutes a criminal negligence not to encourage and assist in every possible way chemical and physical research, even if it should appear to be concerned with subjects having little immediate connection with practical life. As the field of operations of the Electrical Engineer expands, fresh problems are presented for solution which can only be solved by careful and persistent scientific research. We can no longer afford as a nation to sit down and watch other communities solve those problems, and then reap the material advantages of that work for themselves. We must be up and doing. We must anticipate events, and strive always for better things. This implies that in connection with all industries, and especially electrical engineering, there must be a continual search for new things, new methods, and greater achievement. One of the great disadvantages of Government control, or what is commonly called "Nationalisation," is that the men then in actual charge are not sufficiently progressive or eager to break new

ground. They like to go easily, to watch others grapple with difficulties and then to come in when the way has been made quite smooth. As a result, Government technical work is generally behind the times and new methods and appliances are only adopted long after they have been known to, or even discarded by, private enterprise. In the following pages we shall attempt to show the manner in which the electrical industry is based essentially on, and advanced by, pure scientific research, and also the manner in which technology repays its debt to pure science by providing new materials or appliances or larger opportunities for experiment, and so advances our knowledge of the processes at work in Nature. A classical and oft quoted instance of pure scientific research yielding technical applications of immeasurable value is that of the discovery of the generation of an electric current by a moving magnet or by the inductive action of another adjacent current. When in the autumn days of 1831 Faraday first thrust a bar magnet into the interior of a spiral helix of copper wire and found that it created therein an electric current, even he did not foresee the enormous benefits this purely scientific discovery was destined to bestow upon the world. Faraday reserved, and rightly so, his unsurpassed powers of investigation for the discovery of new scientific facts and laws, and he left it to others to make what application they pleased of them. It was not long before this great discovery of Faraday was used by others in the construction of rudimentary forms of induction coil and magneto-electric machine. These by slow stages developed into our modern transformer and dynamo. Instances, however, are not rare of inventions made directly for technical purposes being found later on to have valuable applications in pure scientific research.

One notable case is that of the syphon recorder and mirror galvanometer of Lord Kelvin, invented directly as appliances for receiving signals through long submarine cables in the early years of this enterprise. Now in a

modified form they are found in every physical laboratory as indispensable instruments for scientific research. The magneto-telephone of Bell and the thermionic valve of the writer were in the same manner invented for a technical purpose but found to be of great use in pure scientific investigations. As it would be difficult to deal with the subject of the relation of pure scientific research to electrical engineering apart from specific instances, the objects in view can best be attained by discussing a limited number of branches or special departments of electrical engineering and endeavouring to show in each and all of them that technical advances have, in general, been due to previous or contemporary scientific investigations which have, at the time they were made, no other aim than that of a disinterested advancement of scientific knowledge. Each of the above lectures dealt with, and each chapter of the present book, will therefore deal with one such department of electrical technology and explore its scientific basis.

CHAPTER I

ELECTRICAL INSULATION AND CONDUCTION

All Electrical Engineering is based on the fundamental fact that electricity can move freely over or through certain materials but not through or over others. There is no very sharply marked division between the first class, which are therefore called *conductors*, and the second, called *insulators*, or *non-conductors*, but there is an enormous difference in this respect between good conductors, such as copper or silver, and materials such as sulphur, glass or resin, which are good insulators. To express numerically the number of times by which the electric conductivity of silver exceeds that of sulphur we should require to write down the figure 1, followed by 21 cyphers

Air and gases in a normal condition are also good insulators, and but for this convenience the difficulties of the electrical engineer would be vastly increased. The discovery of this important difference between material substances, like many others in science, was made by an amateur. Stephen Gray, a pensioner of the Charterhouse, aided by his friend, Granvile Wheler, in 1729, stretched a long linen thread, upheld by silk supports, and found that if a brass ball was attached to one end of the thread, which was several hundred feet in length, and a glass rod, electrified by friction, put in contact with the other end of the thread, the electric state travelled along the thread and communicated to the ball the power of attracting small feathers or fragments of paper just as did the excited rod. If, however, metal wires were substituted for silk as the supports the linen thread no longer conveyed any electrical state to the distant ball. This led to the recognition that whilst the electric charge could

escape from the thread by the metal wires, it could not do so when silk fibres were used as supports in place of metal. From and after this date (1729) it was recognised that some substances conduct electricity or allow it to travel through them, whilst others insulate or prevent its movement.

Faraday called the latter class *dielectrics.*

Electricity in motion is called an electric current, and the effective cause of a current is called electromotive force.

A very remarkable characteristic of electric phenomena is the dual nature of this physcial agency. It has been known from antiquity that friction of certain substances, such as resin, amber, or glass, puts them into a condition in which they attract light objects, such as small feathers or bits of straw. The discovery was, however, made in 1733 by that brilliant French genius, Charles François de Cisternay Dufay, that there are two kinds of electricity, and that the electrification produced on glass by rubbing it with silk is different from that produced on resin or amber by rubbing it with flannel. These two kinds were found to destroy or neutralise each other's effects. It remained for Faraday to prove by exhaustive experiments that one kind could never be generated without at the same time bringing into existence an equal quantity of the other. These experiments are described in the eleventh and twelfth series of his *Experimental Researches on Electricity and Magnetism.* The names formerly given by Dufay to these two kinds of electrification, viz., Vitreous and Resinous, have now long been replaced by the terms Positive and Negative.

The two, however, are not merely different in the sense that $+x$ differs from $-x$ in algebra. There is a qualitative difference to which Faraday paid great attention. At the end of the nineteenth century the great discovery was made by Sir Joseph Thomson that negative electricity is atomic in structure—that means there is a small indivisible unit of it, now called an *electron,* and any larger quantity is

made up of an integer number of these electrons. Great attention has therefore been paid to the determination of the quantity of electricity represented by 1 electron. The most exact result is probably that of Professor R. A. Millikan, viz., that the charge of 1 electron is $4{\cdot}774 \times 10^{-10}$ of an electrostatic unit of electricity, or otherwise that the quantity called 1 coulomb, equivalent to the quantity conveyed by a current of 1 ampere flowing for 1 second, is equal to $6{\cdot}3 \times 10^{18}$ electrons. This atom of negative electricity is assumed to occupy a certain volume and to have gravitative mass. The ratio of its charge e to its mass m has therefore been the subject of careful enquiry, and reckoning the charge e in electromagnetic units (E.M U), it is equal to $4{\cdot}774 \times 10^{-10}$ divided by 3×10^{10} $= 1{\cdot}591 \times 10^{-20}$ E M.U The mass m is $0{\cdot}899 \times 10^{-27}$ gram., and the ratio of e/m is 1769×10^{4}. We have not yet been able to isolate so completely the unit or atom of positive electricity, but it is called a *proton*, and there are some reasons for thinking that a chemical atom of hydrogen gas consists of one proton and one electron revolving round their common centre of mass.

Now from electrochemical facts discussed in Chapter VII. of this book, it is known that the ratio of charge to mass for an atom of ionised hydrogen, that is, for a single proton in the same electromagnetic unit as above, is given by the number 9649·4.

Furthermore, it can be shown that the electric charge of a proton is equal to that of an electron only opposite in sign, that is, in direction of electric force. The conclusion then follows that the gravitative mass, or what is commonly called the weight of the proton, is about 1,800 times greater than that of the electron. This establishes one striking difference between the so-called positive and negative electricity The much greater mass of the proton may be due to it possessing a much less bulk than the electron.

The researches made during the last quarter of a century have given a large amount of confirmation to the

view that the chemical atoms of material substances, of which about eighty-eight kinds are known and ninety-two possible, are structures built up of protons and electrons in rapid motion The protons are held together in a very compact mass, called the nucleus, by a cement of electrons, but the protons predominate in number Then around this nucleus, in orbits of various radii and planes, rotate the planetary electrons, these orbits being called the K, L, M orbits, etc., reckoning from the innermost The number of these rotating electrons is called *the atomic number*.

There appear to be always 2 planetary electrons in the innermost or K orbit, and there is an endeavour or desire on the part of the atom to make up the number in the outermost orbit to 8. The atoms of atomic number less than 10 are, however, exceptions to this rule.

The nucleus of the hydrogen atom consists of 1 proton and 1 planetary electron rotating round it The *atomic number* is therefore 1 and the atomic weight is 1 also. The next in order is the helium atom. Its nucleus consists of 4 protons held together by 2 electrons, and there are 2 planetary electrons. The atomic number is therefore 2 and the atomic weight 4 on the hydrogen scale. The atom is also electrically neutral. In atoms with large and complex nuclei, such as Thorium, Uranium, Radium, etc , the nucleus from time to time breaks up. It then ejects electrons called *beta* particles, and helium nuclei called *alpha* particles. It appears then that the helium nucleus is a constituent of the nuclei of many other atomic nuclei. It is one of the toughest objects in nature and has been much used as a projectile to smash up other atoms. Thus the oxygen atom has an atomic weight of 16 and an atomic number 8 Its nucleus must therefore contain 16 protons held together by 8 electrons equivalent to 4 helium nuclei bonded together by their electrical attractions. It has 8 planetary electrons, 2 in the inner or K ring, and 6 in the L ring.

It is therefore greedy to take up 2 more electrons to

complete the outer orbit to 8 electrons, and whe acquire them it becomes an oxygen *ion* chargec units of negative electricity. In the case of the atoms there appear to be 1, 2 or more electrons outer orbits which the atom is not anxious to ret by getting rid of it or them it reduces its outer orb desired condition of 8 electrons.

Thus the atom of sodium has a nucleus comp 23 protons and 12 electrons, and its atomic w therefore 23 and atomic number 11. It has a circle of 11 planetary electrons, 2 in the K orbit, L orbit, and 1 loosely attached electron which the valency electron. It is quite ready to part v latter electron, and it then becomes a sodium *ion* single positive charge of 1 unit, but with 8 p electrons on its outer orbit. Again, the element has an atomic weight of 35·46 and an atomic nur It has always been a puzzle why certain elemer fractional atomic weights but integer atomic n It appears, however, that since the nucleus can 1 proton and 1 electron equivalent to a hydro without altering its atomic number but yet decre atomic weight, that we can have atoms of d atomic weight but the same atomic number, ar are called *isotopes*. Now, it has been shown by D Aston that there are two kinds of chlorine atom atomic weight 35 and the other of atomic weight 37, both have the same atomic number, viz., 17. C chlorine gas is a mixture of these two chlorine iso a certain proportion The planetary electrons in are 2 in the K orbit, 8 in the L orbit, and 7 in the]

The chlorine atom therefore desires to take more electron to make 8 in its outer ring. V achieves this aim it becomes a chlorine ion with negative charge.

It appears, however, that this desire to comp outer octet of electrons can be satisfied by two a opposite kind, putting together their valency e

and holding them in common. Thus an atom of sodium meeting an atom of chlorine comes to some bargain that the valency electron of sodium shall be considered to belong as well to the chlorine. Each atom then acquires a unit electric charge of opposite sign and yet each atom satisfies its octet appetite or desire to have 8 planetary electrons in its outer orbit.

In metals the valency electron or electrons are very easily detached, and appear to change their atomic residence very often. Thus there are supposed to be free electrons mingled with the atoms and positive ions. We shall consider presently the evidence for and against this view

For every free electron in a monovalent metal there must be an atom which has lost an electron and therefore become a positively charged ion. Hence in metals we may have three kinds of particles present, viz., complete electrically neutral atoms, positively charged metallic ions with 1 or more unit charges, negatively charged ions, and perhaps also free negative electrons

The atoms, however, are not mingled in disorderly fashion but built up into arrangements called *lattices*, and these into crystals, although the crystals may be oriented in an irregular manner. By the employment of X-rays it has been found possible to determine the form of these lattices, and the arrangement of atoms in a crystal. Thus in a crystal of common salt or sodic chloride each atom of sodium is surrounded at equal distances by 6 atoms of chlorine, and each atom of chlorine by 6 atoms of sodium The atoms thus occupy the corners of cubes, called a cubic lattice, and we cannot say that any one atom of chlorine belongs particularly to 1 atom of sodium. The atoms forming the lattice are held in position by the attractions of their opposite electric charges, and together form the compound sodic chloride.

In materials, such as shellac, glass, ebonite, india-rubber or gutta percha, which include those called good insulators, the molecules are very complex in structure.

There are many atoms combined into bulky molecules and molecules into lattices and perhaps crystals.

It appears that free electrons do not exist in these substances or cannot move easily through the complex molecules, or at least are very few in number.

These two classes of solids, viz. the good conductors and the good insulators, differ in their behaviour under the action of electromotive force

If the terminals of a voltaic battery or electric generator of any kind are applied to the ends of a piece of metal the valency electrons in their irregular excursions from atom to atom are caused to drift in the opposite direction to the electromotive force under the ordinary convention. They do this by jumping from atom to atom. They move towards the positive terminal or electrode of the battery. The metallic atoms and ions in the metal do not drift.

This drift of electrons is called a *conduction current* and is characteristic of the motion of electricity in metals and such substances as graphite, boron, selenium, and a few others.

If, on the other hand, an electromotive force is applied to a substance which is an insulator, the complex molecules or atoms undergo a strain or displacement or some change of form which is called a displacement current, but there is very little true conduction current. The insulator under electric force behaves like an elastic substance under mechanical force. It is strained, but when the force is removed the strain vanishes.

Moreover, there is another point of resemblance. If an elastic substance, such as a steel rod, is stretched beyond its elastic limit it yields and breaks. So also the insulator under electric stress. There is a limiting stress beyond which it breaks and is pierced by the voltage. This is called the breakdown voltage (B D.V.) for a given thickness of the material. Since, then, an electric current consists in a procession of electrons, its transmission requires a path or conductor through which they can

move, but the electrons must be prevented from straying into places where they are not wanted by covering the conductor with an insulator through which they cannot move, just as traffic is facilitated along a well-made road, but prevented from diverging into the surrounding areas by fences or hedges.

Accordingly, the large use of electric currents has necessitated a vast amount of scientific research to investigate the properties and improve the qualities of both non-conductors and conductors of electricity.

Considering, then, first the insulators, we shall briefly describe those researches directed to determine (i.) the dielectric coefficient; (ii.) the dielectric strength or breakdown voltage, (iii.) the insulation resistance or its reciprocal the insulation conductivity; and (iv.) the researches directed to improving the mechanical qualities of insulating materials. The first quality or the dielectric coefficient is the ratio of the electric displacement or strain, measured in a certain manner, to the electric force in the material. The electric force is measured by the impressed voltage per centimetre of thickness of the material. It may be explained in another way. Suppose a metal sphere of radius R to be enclosed concentrically in a hollow spherical metal shell of inner radius R′. Let a quantity of positive electricity Q units be placed on the inner sphere. It will create by induction an equal quantity (— Q) of negative electricity on the inner surface of the spherical shell. The arrangement forms what is called a condenser. The insulating material, air or anything else, in the interspace between the sphere and the shell was called by Faraday *the dielectric.* If the inner sphere is charged with a certain electric quantity, and if there is a certain potential difference measured in volts or other units between the sphere and the shell, then the ratio of the electric charge to this potential difference is called the *capacity* of the condenser.

This capacity as shown, first by Henry Cavendish and later by Faraday, depends upon the nature of the di-

electric. The ratio of the capacity of such a spherical condenser with the interspace wholly filled by some dielectric to its capacity when the interspace is filled with air or is a vacuum, is called the dielectric coefficient of that insulator.

The numerical value of this coefficient for any material varies appreciably with the physical state, and very much depends on the temperature, and especially on whether the electric force is steady in one direction or alternating. And if the latter, then on the frequency or on the number of times it is reversed per second. Owing to variations in quality of substances called by the same name, such as glass, indiarubber, etc., it is seldom useful to express this dielectric coefficient, as is sometimes done, to three or four places of decimals unless the particulars under which it is determined are carefully specified. The practical problems on which these measurements of the dielectric constant have most bearing are on the construction of electric condensers and the manufacture of cables for transmission of alternating electric currents. For the condensers, other things being equal, we require an insulator with as high a dielectric constant, and in the cables an insulator with as low a dielectric constant, as possible. The choice of material for the insulator has, however, to be controlled by the condition that the substance must have a sufficient dielectric strength or B D.V for the purpose in view, and also that the energy losses in it due to conduction or hysteresis must be as small as possible. In a condenser of capacity C, subject to alternating electromotive force, and of frequency n, there is a current flowing in and out of the condenser called the capacity current. If the electromotive force varies in accordance with the ordinates of a sine curve, that means that the potential difference or electric pressure v between the metal plates or elctrodes of the condenser at any instant is equal to the maximum potential V difference multiplied by the numerical value of sin $2\pi nt$, where t is the time reckoned from the instant of zero potential difference to the instant considered, then

the capacity current at that instant is measured by $2\pi n CV \cos 2\pi nt$, where C is the capacity of the condenser.

The capacity is proportional to the dielectric constant of the insulating material. The above formula shows that the capacity current is not in step with, but differs in phase 90 degrees from the impressed electromotive force, provided there is no energy loss in the dielectric due to conduction or other cause. Suppose then that we desire to make simply a condenser. It is desirable to select as a dielectric a material with as large a dielectric constant but as small an energy loss and as large a specific resistance and breakdown voltage as possible. If, however, we are insulating a cable to be used to transmit alternating currents, then we must choose an insulating material which has as small a dielectric constant and as small an energy loss as possible, but as high a breakdown voltage as may be obtainable.

The reason for requiring as small a capacity as possible in the case of a cable is to make the capacity current small, because that current is transmitted along the copper conductors and dissipates power in them as heat proportional to the square of the current These very various and often incompatible requirements in electrotechnical work have necessitated an immense amount of scientific research to determine these various specific qualities in known insulators, and to discover new artificial dielectrics which have the necessary qualities.

It may be noted at this stage that the majority of natural, common or easily obtained insulating materials have very poor mechanical qualities. They are brittle, not easily worked with tools, will not take screws, or else are too soft, easily melted, and deteriorate rapidly when exposed to moisture, light and air Thus, sulphur, though an excellent non-conductor, has the above-mentioned defects ; glass, porcelain, ebonite, mica, have also the same rather objectionable qualities.

Gutta percha is rapidly deteriorated by the action of light and air, though very permanent under sea-water.

All fibrous materials, such as cotton fibre and cellulose generally, are very hygroscopic, and when exposed to moisture the water vapour condenses in the fibre tube in consequence of a capillary effect, explained fully in Clerk Maxwell's book, *Theory of Heat*, p. 287.

Accordingly, all fibrous material, such as paper, card, calico, linen, hemp, red and black fibre, deteriorate very rapidly in insulating power when exposed to air, but when perfectly dry they are fairly good insulators

Other materials, such as glass and porcelain, condense water vapour on their surface into a film of water more or less discontinuous.

Hence we have to distinguish between the mass conductivity of these materials and the surface leakage of electricity over them Moreover, there is a very rapid variation of mass conductivity with temperature. Most of these dielectrics increase rapidly in electric mass conductivity with rise of temperature. The numerical values for the specific resistance of insulators given in most text-books are therefore of little value because they do not take into account the relative mass and surface conductivities, nor the variation with temperature and time. Furthermore, the contact resistance at the place where the metallic electrodes touch the dielectric is an important part of the measured value.

Again, many of the methods used for dielectric resistance measurement are defective in that they assume that the materials as conductors obey Ohm's law and have a resistance independent of the current passing, which is not the case. The author has accordingly devised a method of measuring insulation resistance, which makes no assumption that it obeys Ohm's law and also enables the body, surface and electrode contact resistance to be separated out. It is as follows: Two large condensers, C_1, C_2, of equal capacity, about 5 microfarads or more, are joined in parallel, and each condenser discharges through a separate resistance, R_1, R_2 (see Fig. 1). An electrostatic electrometer, V_1, such as that of Dolezalek, is con-

nected between the two condenser terminals on the same side.

If the condensers are charged to the same potential and then allowed to discharge, the electrometer will show no deflection if the two resistances are exactly equal in every respect, because its terminals fall in potential at equal speed and are always equal.

If, however, the resistances differ in any respect, then

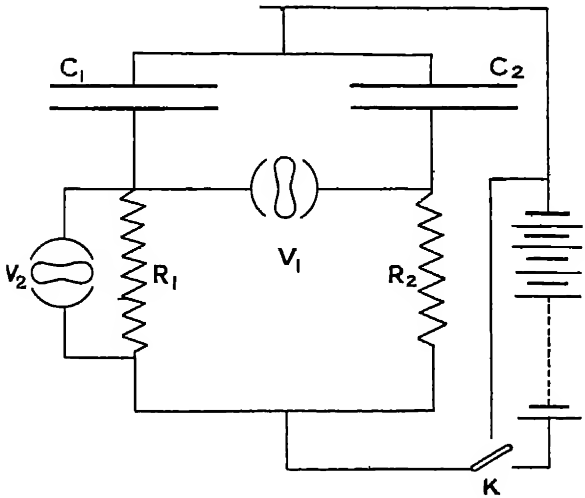

FIG. 1.—Arrangements for determining body and surface conductivity of dielectrics

the electrometer deflects, and if we take observations of it at equal intervals of time we can plot a curve of potential taken at observed intervals of time. The slope of this curve can be measured at numerous points and another curve plotted, the ordinates of which show the product of the condenser capacity C and the time rate of change dv/dt of the electrometer reading (see Fig. 2). This gives us the current flowing through a resistance equal to the difference of the two resistances, R_1, R_2. We can then by another electrostatic voltmeter, V_2, measure at the same instant the potential difference V of the ends of

one of these two resistances, say R_1. We have then a numerical value of the current due to the difference of R_1 and R_2 and the P_1 D_1 at its ends. Hence $V \div C \frac{dv}{dt} = r$ is the difference of the two resistances, R_1 and R_2. Suppose, for instance, that R_1 and R_2 represent two short rods of celluloid, each say 3 cm. in length, the section of one of them being a square of 1 cm. in side and the other a rectangle of sides 1·5 cm. and 0·5 cm. Then they have equal perimeter and surface, but the cross section of the first is 1 sq. cm. and of the other 0·75 sq. cm.

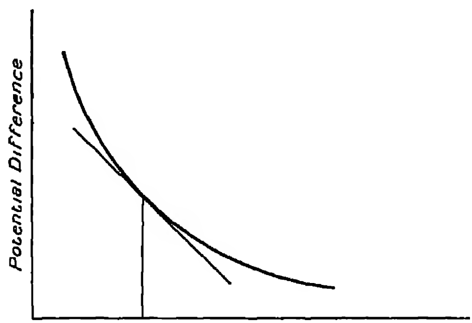

FIG 2.—Method of determining time rate of change of potential from electrometer deflections at observed times.

Hence the latter has greater body resistance than the former.

An experiment made as above described would therefore show a difference in effective resistance. But that difference could not be due to surface leakage, because it is equal in the two cases. It must be due to the body resistance. In this manner we can separate out and measure for various insulating materials their relative surface and body resistances.

Thus, for the above example, the measurements would give the body resistance of a prism of celluloid 3 cm. in length and $1 - 0{\cdot}75 = 0{\cdot}25$ sq. cm. in section unmixed with any effect due to surface leakage.

The aldehydes are products of the oxidation of alcohol and have the general formula R,CHO, whereas the alcohols are of the type R,CH_2OH, where R is some carbon group or radicle. Formaldehyde, H,CHO, an oxidation product of methyl alcohol, is a gas soluble in water and was put on the market as a commercial product about 1891. Phenol, otherwise called carbolic acid, is a fine white crystalline material obtained during the fractional distillation of coal. If these substances are heated together with the addition of some other material—acid, alkaline, or neutral, called a catalyst—a substance is formed known as a synthetic resin. If heat is applied for a short time the material becomes a treacle-like sticky liquid or solid melting at about 80° C If prolonged heating is given it changes into an infusible solid material, which can be heated to 250° C. without damage. This solid synthetic resin is an excellent insulator. The study of these synthetic resins was undertaken by Dr. L. H. Baekeland some years ago, and they are now known commercially as Bakelite. The liquid form is called Bakelite A and the solid Bakelite B. In its purest state the solid has a chemical formula $C_{42}H_{42}O_9$. It is a light yellow solid of specific gravity 1·25, non-absorbent of water, tough, and can be heated without injury to 300° C. It has a very high dielectric strength of 400,000 volts per centimetre or more It can be moulded to required shapes and cut and turned. It dissolves in acetone and alcohol, and can then be used as a varnish or for impregnating dry paper or cloth or cotton covering of copper wire.

There are a great variety of these synthetic resins now on the market in the form of rods, tubes, insulators of various shapes, and the material has been a great addition to the resources of the electrical engineer.*

Other useful dielectrics which research has discovered

* The samples shown at the Lectures were kindly supplied by Messrs Attwater & Sons, Hopwood Street Mills, Preston, England, who are large manufacturers of "Bakelaque Insulation," an improved synthetic resin

are employed. These oils differ immensely in the electric force required to break them down and make a spark pass through them. Moreover, it has been found that very small traces of water or floating dust or fibres in the oil very greatly reduce its dielectric strength. It is accordingly tested by placing the oil in a glass or quartz vessel and immersing in it two brass balls carried on wires. These balls are ½ in. in diameter, and the gap between their nearest surface is 0 15 inch. A gradually increasing alternating voltage with a frequency of 50 cycles is put upon the balls and the potential difference at which a spark passes between them is measured by an electrostatic voltmeter. A good oil stands 30,000 to 40,000 volts across this 0·15 in. gap and, if specially purified, may even rise to 100,000 volts per 0·15 in. gap.

The electric strength falls with great rapidity with the introduction of the slightest trace of moisture or impurity, so much so that even putting the human fingers into a purified oil will bring down the electric strength notably.

The breakdown of an insulating oil is caused by the movement towards the gap of minute particles of water or dirt due to the variable electric field. If particles of iron having a higher magnetic permeability than air are placed in between two magnetic poles in a field of variable strength, they will be moved in the direction in which the field increases most rapidly with a force proportional to the field and to its rate of change in that direction. The same is true of dielectrics in a variable electric field. The particles of water having a high dielectric constant (80) are drawn into the region of strongest electric field between the balls with a force proportional to that field and to its rate of increase in that direction. The water and dirt particles make a bridge of low resistance between the balls, and then an electric discharge passes breaking down the insulation of the oil. The same thing happens inside the iron tanks full of oil in which transformers, switches or condensers are immersed in a high voltage

The aldehydes are products of the oxidation of alcohol and have the general formula R,CHO, whereas the alcohols are of the type R,CH_2OH, where R is some carbon group or radicle. Formaldehyde, H,CHO, an oxidation product of methyl alcohol, is a gas soluble in water and was put on the market as a commercial product about 1891. Phenol, otherwise called carbolic acid, is a fine white crystalline material obtained during the fractional distillation of coal. If these substances are heated together with the addition of some other material—acid, alkaline, or neutral, called a catalyst—a substance is formed known as a synthetic resin. If heat is applied for a short time the material becomes a treacle-like sticky liquid or solid melting at about 80° C If prolonged heating is given it changes into an infusible solid material, which can be heated to 250° C. without damage. This solid synthetic resin is an excellent insulator. The study of these synthetic resins was undertaken by Dr L H. Baekeland some years ago, and they are now known commercially as Bakelite. The liquid form is called Bakelite A and the solid Bakelite B. In its purest state the solid has a chemical formula $C_{42}H_{42}O_9$ It is a light yellow solid of specific gravity 1·25, non-absorbent of water, tough, and can be heated without injury to 300° C. It has a very high dielectric strength of 400,000 volts per centimetre or more It can be moulded to required shapes and cut and turned. It dissolves in acetone and alcohol, and can then be used as a varnish or for impregnating dry paper or cloth or cotton covering of copper wire.

There are a great variety of these synthetic resins now on the market in the form of rods, tubes, insulators of various shapes, and the material has been a great addition to the resources of the electrical engineer.*

Other useful dielectrics which research has discovered

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are the Acrolein Gels. Acrolein is the aldehyde of allyl alcohol. Its composition is $CH_2CH(CHO)$, and being an unsaturated molecule it can form additive compounds, some of which are solids with great insulating powers They were discovered by MM. C. Moureau and C. Dufraise in the course of researches on Acrolein. It is a hard, yellow, amber-like solid which can be turned, bored, or moulded, and is non-hygroscopic, but only suitable for use at temperatures below 100° C.

A third very useful artificial dielectric is Acetyl Cellulose, which has various trade names such as Cellon or Cellite. Cotton when treated with strong nitric and sulphuric acid is converted into trinitrocellulose or gun-cotton. This can be dissolved in camphor and forms the material called celluloid. This latter is, however, a very inflammable substance. It was discovered that a similar compound, tri-acetylcellulose, can be formed by using anhydrous acetic acid in place of nitric acid. This also can be dissolved in camphor and makes a substance like celluloid, but non-inflammable. It can be rolled into sheets and has a dielectric constant of about 4·5, and a dielectric strength of 20,000 to 30,000 volts per millimetre of thickness. It can therefore be used in making condensers, and has many advantages compared with most other insulators, such as glass, mica, celluloid, or ebonite.

It will be seen, therefore, that scientific research has come to the aid of electric technology by giving us new insulating materials with special necessary qualities which are of great value.

Another direction in which research has been important is in improving the breakdown voltage of insulating oils. The electrical transmission of power over long distances is entirely dependent on the employment of very high voltages The transformers used to step-up the voltage of the generating machines to the voltage put upon the transmission lines must all be insulated by being immersed in oil.

For this purpose special kinds of resin or mineral oil

are employed These oils differ immensely in the electric force required to break them down and make a spark pass through them. Moreover, it has been found that very small traces of water or floating dust or fibres in the oil very greatly reduce its dielectric strength. It is accordingly tested by placing the oil in a glass or quartz vessel and immersing in it two brass balls carried on wires. These balls are ½ in. in diameter, and the gap between their nearest surface is 0·15 inch. A gradually increasing alternating voltage with a frequency of 50 cycles is put upon the balls and the potential difference at which a spark passes between them is measured by an electrostatic voltmeter. A good oil stands 30,000 to 40,000 volts across this 0·15 in. gap and, if specially purified, may even rise to 100,000 volts per 0·15 in. gap.

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electric supply station unless the oil is frequently purified to free it from water and dirt.

This purification is best attained by passing the oil through a centrifuge, such as that of de Leval. In this machine the oil is rotated at a high speed, the portions which contain the water and dirt, having a higher density than the pure oil, are flung outwards and separated.

The testing, filtering, heating and dehydration of the insulating oil used is an important part of the daily routine of a high tension electric station.

In addition to the above special insulating materials a large number are used, the essential basis of which is cellulose in the form of paper in sheet or compressed paper pulp, which may or may not have been "parchmentised" by being treated with sulphuric acid. These cellulose insulating materials are, however, of limited use in electrotechnics unless they have been dried in vacuo at a temperature of about 120° C. to drive out moisture from the fibres and then impregnated under pressure with some resinous or oily fluid, or bakelite solution in alcohol, and then varnished on the surface with a hard-drying non-absorbent insulating enamel or varnish.

Finally, it may be said that but for the extensive research that has been prosecuted in connection with the preparation and testing of insulators of high dielectric strength and good mechanical qualities the distribution of electric current at high voltages for the transmission of power would have been impossible.

This is especially the case in connection with high voltage underground cables. Whilst gutta percha is the only insulator so far found suitable for submarine telegraph cable insulation and vulcanised indiarubber the best for insulating house wiring for electric light, experience has shown that resin-impregnated manilla paper or jute enclosed in an air-tight lead sheath forms the best means of insulating underground cables for large currents and high voltages. Such cable is armoured with steel wires to give it mechanical strength. If we consider a

single copper conductor so insulated, the electric force in the dielectric is inversely as the distance of the point from the axis of the conductor. Hence the suggestion arose that it would be advantageous to employ a *graded* insulation, viz., an insulating material in layers, the layers next the conductor having the greatest dielectric strength and the outer layers the least.

The reason for such grading is that if a uniform dielectric is employed of strength sufficient to secure from piercing in the layer next the conductor it would be unnecessarily strong at the outer layer.

There are some difficulties in the way of carrying out this grading in practice.

Another plan intended to assist the manufacture of extra high tension cables is the introduction of metallic inter-sheaths.

Experiment has shown that the dielectric strength of a thin layer of an insulator is greater than that of a thick layer.

Thus, if a certain thickness of resin-impregnated paper, say 1 mm., is pierced by 5,000 volts, then it is found that a sheet 2 mm. in thickness would not stand 10,000 volts, but perhaps only 8,000 to 9,000. Again, a sheet 3 mm. in thickness of the same material would be pierced by much less than 15,000 volts, perhaps by 12,000.

Hence the quotient of voltage by thickness, which is a measure of the breakdown electric force in the material, decreases as the thickness increases.

The reason is probably that the molecules on the surface of a solid are drawn closer together than those in the interior, and there is on every solid a sort of skin which is less easily broken through electrically than the interior portions.

Accordingly, we can build up a stronger dielectric by separating it into thin sheets, separated by conducting layers, than when made in one mass of the same total thickness. The employment of inter-sheaths for this purpose in cable dielectrics was therefore suggested

in 1907,* and has been fully
A. Russell, Mr. C J. Beaver, and Major A. M. Taylor.

The method consists in inserting in the insulation of the cable one or more layers of spirally-wound copper tape or thin lead tube so as to divide up the insulation into layers. These metal tapes or tubes are connected back to intermediate tapping points on the transformer secondary circuit supplying the voltage at such points as to make the electric force on the various dielectric layers equal.

This method of inter-sheaths has received careful attention from electrical engineers, and a full discussion of its advantages and disadvantages has been given in Papers by Mr. C. J. Beaver † and Major A. M. Taylor.‡ There is, however, room yet for a large amount of research on the conditions of breakdown or rupture of dielectrics, and also the energy losses in connection with them when insulating alternating electric currents.

In some dielectrics, such as gutta percha, the true conductivity is much higher for alternating currents of telephonic frequency, that is 1,000 and upwards, than it is for steady or low frequency alternating currents. In the case of alternating current cables the phase difference of current and impressed electromotive force is less than 90° C. Accordingly, the current has a component in step with the voltage, and this dissipates power. It is therefore necessary to determine for such cables the *power-factor ;* that means the ratio of the power expended in the cable dielectric reckoned in watts to the product of the capacity current, that is, the current flowing across the dielectric, and the impressed voltage on the cable For various dielectrics this power-factor may lie between 0·01 and 0·1 in numerical value.

* This suggestion appears to have been first made by Professor J T. Macgregor-Morris in a discussion at the Institution of Electrical Engineers in London, on a Paper by Dr A. Russell See *Journal of the Institution of Electrical Engineers*, London, Vol 40, p 50 1907

† See *Journal of the Institution of Electrical Engineers*, London, Vol 53, p 57 1914

‡ See *Journal of the Junior Institution of Engineers*, Vol 34, p 64 1924 Also Vol 35, p 201 1925.

Space will not permit any full reference to all the very valuable scientific research work carried out on dielectrics, but the following memoirs are useful contributions to the subject :—

"High Voltage Tests and Energy Losses in Insulating Materials." By E. H. Rayner. *Journal of the Institution of Electrical Engineers*, London, Vol 49, p. 77. 1912

"The Characteristics of Insulation Resistance" S. Evershed. *Journal of the Institution of Electrical Engineers*, Vol. 52. 1913.

"Dielectric Strength of Insulating Material." Dr A. Russell *Journal of the Institution of Electrical Engineers*, Vol. 40

"The Power Factor and Conductivity of Dielectrics at Telephonic Frequency." J. A. Fleming and G B Dyke, *Journal of the Institution of Electrical Engineers*, Vol. 49, p. 323. 1912.

We must, then, direct attention to the scientific researches on the electric conductivity of good conductors, especially the metals and alloys. It is fortunate that the common metal copper is one of the best electrical conductors, and that it has such ductility and tensile strength that it can be drawn into wires of every degree of fineness and rolled also into sheets. It can also be cast and easily worked with tools.

In the early days of telegraphy it was soon noticed that very minute percentages of certain impurities in it had a very great effect in reducing its electrical conductivity. Taking the conductivity of pure copper to be denoted by 100, then the addition of 0·05 per cent. or 1 part in 2,000 of carbon lowers the conductivity to 80·5. The addition of 8·7 parts of phosphorus to 1,000 of copper causes it to fall to 20·6, whilst 2·8 per cent. of arsenic takes it down to 14·12 per cent., or about one-seventh of its original value.*

Amongst the earliest comprehensive research work on

* See Dr S Arrhenius, "Chemistry in Modern Life" (Chapman, Hall & Co., London)

the electric conductivity of pure metals and alloys was that of Dr. A. Matthiessen, about 1860–61, to which a further reference is made in the last chapter of this book.

It was soon ascertained that the highest electric conductivity exists in absolutely pure metals; and amongst these those with the smallest atomic volumes, such as silver, copper, gold, aluminium, are the best. The atomic volume is the quotient of atomic weight by density and gives us a certain measure of the closeness of the packing of the atoms.

The next matter of interest is that alloys of metals have in general far less conductivity than those of the pure metals forming the alloy.

There is also a striking difference in the effect of temperature on the conductivity of pure metals and alloys. The specific resistance, which is the reciprocal of the conductivity, is the resistance of a unit cube (1 cm. cube) between opposed faces. If this is measured at 0° C. and then again at other temperatures it is found that for pure metals the *temperature coefficient* which is the ratio of the increase in resistance between 0° C. and 1° C. to the resistance at 0° C. is about $\frac{1}{273}$, or rather more, say $\frac{1}{250}$. This fact seemed to indicate that if a pure metal could be cooled to the absolute zero of temperature its electrical resistance would vanish.

The first attempt to put this to the test of experiment was in 1892 by the author and the late Sir James Dewar, as soon as the last named had succeeded in producing liquid oxygen on a large scale. In 1893 a long investigation was published by the same authors, showing the variation in electric resistance of numerous pure metals and alloys. The temperature of liquid oxygen is —185° C., or about 90° K. (absolute).

It became evident from the figures obtained that at the absolute zero of temperature, viz., — 273° C., the electric

resistance of pure metals would become very small or even vanish, but that no such great diminution would take place in the case of alloys of pure metals.

It was not until twenty years later that this theory was put to full test, when liquid helium was first obtained in considerable quantities by the late Professor Kamerlingh Onnes, of Leyden, in Holland, thus giving a liquid of temperature — 269° C. or 4° K. (absolute). Onnes then made the remarkable discovery that certain metals, such as lead, tin, thallium, and mercury, when cooled to that low temperature, lost, even a few degrees above the absolute zero, all electric resistivity and became perfect conductors. In the case of other pure metals, some small measurable resistance remained even at the lowest temperature reached. This resulted in some extraordinary phenomena. For instance, a ring of lead immersed in liquid helium had an induced electric current of 320 amperes created in it by drawing away from it a magnetic pole. This current would at ordinary temperatures have vanished in a fraction of a second. But at that low temperature it continued to circulate in the lead ring for half an hour with a decrease of only 1 per cent. in its strength.

Onnes called these metals *supra conductors*. If such decrease in resistance could be brought about at ordinary temperature by any means, electrical engineering would be transformed. We should be able to transmit enormous amounts of power by means of very small electric currents in conductors of extremely small section.

These scientific researches have found their application in numerous ways in electrical engineering.

For the purposes of electric transmission we require the highest conductivity possible, and this is obtained by the production of soft annealed perfectly pure copper by electrolysis as explained in Chapter VII. of this book. The temperature coefficient of this pure copper is about 0·004. This means that a wire of 1 ohm resistance at 0° C. would have 1·4 ohms resistance at 100° C., or an increase of 40 per cent. This large increase is incon-

venient, but it has one advantage, it enables us to measure the temperature of the wire by measuring its resistance. Professor H. L. Callendar made use of this same property of pure platinum to construct electrical resistance thermometers by which temperature can be measured easily over any range between absolute zero and 1,000° C. The property of alloys of possessing high specific resistance and small temperative coefficient is also of great technical value, as it enables us to make resistance coils of metals which do not change resistance with temperature to any sensible degree.

One of the first of these was the so-called *German silver*, which contains no silver, and probably originated in China and not Germany. It is an alloy composed of 50 to 70 per cent. copper, 10 to 25 per cent. nickel, and 20 to 30 per cent. zinc. Its temperature coefficient is 0·00037, or about one-tenth that of pure copper. Another alloy of less coefficient still is *nickelin*, the composition of which is copper 54 per cent., nickel 25 per cent., zinc 20 per cent. The coefficient is 0·00020.

For making modern resistance coils in measuring instruments we now employ either *Constantan*, composed of copper 58 per cent, nickel 41 per cent., manganese 1 per cent.—coefficient = 0 00003, or better still, *Manganin*, which has a composition—copper 84 per cent., nickel 4 per cent., manganese 12 per cent, and a very small temperature coefficient. The specific resistance of manganin is 44 millionths of an ohm per centimetre cube, but its variation with temperature is very irregular. At about 12° C or ordinary temperature it is 0·000006, and at 25° C, and also at 475° C., it is zero, whilst between these temperatures it has a negative value, that is the resistance decreases instead of increasing with rise of temperature. Accordingly, the material is of great use in the construction of resistance coils for measuring electric resistance, as at ordinary room temperature it is for all practical purposes a material of constant resistance

It is a remarkable thing that whilst all pure metals and

most alloys diminish in electric conductivity when their temperature rises, many metalloids and oxides increase in conductivity with rise of temperature. For instance, boron, graphite, amorphous carbon, and selenium are better conductors when hot than when cold. This is also characteristic of many oxides, such as those of calcium, barium, strontium, magnesium, and the oxides of many rare metals. This, in fact, was the scientific basis of the Nernst electric lamp, now, however, replaced by the metal filament lamp. Selenium has the rare and extraordinary property of having its electric conductivity improved by light falling upon it, so that it has less resistance when exposed to daylight than when in the dark. The possible reason for this will be considered in a later paragraph. This property of selenium has been made the basis of methods for transmitting pictures by telegraph, with wires or without.

It will, then, be of advantage in the next place to consider some hypotheses which have been suggested to explain these powers of conduction and insulation.

W. Weber was the first to surmise that in metallic conductors there are free particles of electricity which are moved by the electromotive force through the interstices between the metallic atoms. This, however, was a mere conjecture until Sir J. J. Thomson had proved, in 1899, that these particles of negative electricity really exist. H. A. Lorentz, Riecke and P. Drude then gave definiteness to this idea by supposing that free electrons exist in conductors. These electrons were assumed to be in rapid irregular motion in all directions, like the molecules of a gas excluded by the metal.

If an E.M.F. is applied to the metal then superimposed on the irregular motion of the electrons it is asserted usually there is a steady drift of electrons in one direction, viz., from the negative electrode or cathode to the positive or anode. If we make the assumption that the energy represented by the sensible heat or temperature of the solid is equally divided between all

the degrees of freedom of the atoms and electrons, and that the free electrons behave like the molecules of a gas, we can easily arrive at a mathematical equation, which shows that the electric resistance should be independent of the electromotive force, and in magnitude be directly proportional to the absolute temperature.

It may be mentioned that by number of degrees of freedom we mean the different ways in which the energy motions or displacements can take place. Thus the atoms of the solid have three degrees of kinetic energy, viz., the three x, y, z components of any motion, also three degrees of potential energy corresponding to the three displacements along these axes. The free electrons have only three degrees of kinetic energy, because they have no potential but only kinetic energy.

The assumption made is that these free electrons behave like the molecules of a gas and have their velocities of translation distributed according to the same law as that of gas molecules

The fundamental gas law is that the pressure (P), volume (V) and absolute temperature (T) are connected by the relation, $PV = RT$, where R is called the *gas constant*. If we take V to be the volume of a gram-molecule or gram-atom, that is, of a number of grams weight equal to the molecular or atomic weight, then it is easy to show that $R = 83{\cdot}2 \times 10^6$. For the molecular volume of a gas at 760 mm pressure (which is nearly 10^6 dynes) and 0° C temperature (which is 273° absolute) is 22,400 c.cm. Now the product PV is of the dimensions of work or energy, and hence R is to be reckoned in ergs or calories. But 1 calorie, which is the heat required to raise 1 gm. mass of water 1° C., at about 4° C. is equal to 42 million ergs. Therefore, $R = 1{\cdot}985$, or, say, 2 calories. If we take u to be the square root of the mean of the squares of the velocities of the gas molecules or the so-called R.M.S. velocity, then it can be shown that $\frac{3}{2}RT$ is equal to the molecular kinetic

energy in 1 gram molecule. Accordingly, $\frac{1}{2}$ RT is the kinetic energy per degree of freedom as regards kinetic energy or energy of translational motion In the case of a monatomic gas like argon, in which there is only energy of atomic translational motion, the energy per gram-atom should be $\frac{3}{2}$ RT. The specific heat at constant volume is the energy absorbed per degree rise of temperature, and for the gram-atom is therefore equal to $\frac{3}{2}$ R, or to 3 calories. This is found by experiment to be the case for the atomic heat of argon and of monatomic gases generally. In the case of solids the atomic heat, or product of atomic weight and specific heat, should then be 6 calories, corresponding to the 3 degrees of kinetic and 3 of potential energy of the atoms.

Now by Dulong and Petit's law the atomic heat is found experimentally to have a value near to 6. If, however, the electrons shared equally in the atomic energy, then the atomic heat should be 9 instead of 6 This seems to indicate that the electrons do not share equally with the atoms in the heat energy. The atomic heat of a solid varies, however, very much with temperature of the body.

It is therefore a matter of very great scientific importance to obtain more direct proof whether these free electrons do exist in good conductors.

An indirect proof is found in the thermionic phenomena, which will be discussed in a later chapter.

Meanwhile we may mention certain experiments based on the fact that these free mobile electrons, if they exist, have mass as well as electric charge.

If, for instance, a long metal rod is moving forward in the direction of its length with great velocity, and if it is suddenly arrested, the free electrons in it should lurch forward like the passengers in a train when it suddenly stops. This implies that the front end of the rod should

become slightly negative in charge compared with the rear end, and that if the two ends were connected a small transitory electric current should be found to exist.

An experiment of this kind was described by Messrs. R. C. Tolman and Stewart in 1916 (see *Physical Review*, Vol. 8, p. 97, also Vol. 9, p. 164 (1917)).

They rotated a circular coil of insulated wire in its own plane and suddenly arrested its motion by a brake. The ends of the coil were connected through slip rings with a sensitive galvanometer. When all corrections were made, they found that at the instant of stoppage of the coil a small current of negative electricity moved forward in it.

In a second set of experiments by Messrs. Tolman, Karrer, and Guernsey (see *Physical Review*, Vol 21, p. 525 (1923)) a different method was adopted, a copper cylinder placed with its axis parallel to the earth's magnetic field was rocked to and fro around this axis. If there are free mobile electrons in the metal there must also be an equal number of positively charged atomic ions, that is, neutral atoms which have lost an electron.

When the cylinder is vibrated round its axis, the motions of the freely movable electrons and those of the fixed ionised atoms are out of step with each other. The cylinder was surrounded by a stationary coil of insulated wire connected through a thermionic amplifier with a vibration galvanometer.

When the cylinder was oscillated rapidly a small induced current was found to appear in the vibration galvanometer. These researches were repeated with extra precautions by Messrs. Tolman and Mott-Smith, in 1926 (see *Physical Review*, Vol. 28, p. 794 (1926)). The experiments are undoubtedly very difficult to carry out in such manner as to eliminate all spurious effects. The actual mass of the free electrons present is extremely small. The electron has only 1/1800 of the mass of a proton and the number of protons in an atom is numerically equal to its atomic weight. Accordingly, an atom of copper has $63 \times 1{,}800 = 113{,}400$ times the mass of an

electron If, then, the number of free electrons is ε equal to the number of atoms, which for copper is a 10^{23} per cubic centimetre, the total mass of free elec would be only one hundred thousandth of the mass c metal. Hence, in a mass of copper occupying a bu about 12 cub. cm. and weighing therefore about 100 the total weight of all the free electrons, assuming the be 1 per atom, would only be 1 milligram.

Experiments to prove the existence of inertia due t electrons in conductors are therefore successively diff and up to the present the experiments of Tolman an co-workers have not been repeated and confirmed. view that the free electrons share equally with ato the heat energy, in other words the theory of the equi tion of the energy leads to conclusions which are op to observed facts.

In solid metals the atoms are arranged in ce regular forms, called lattices, and the lattices are bu into small crystals, but these crystals may be, generally are, irregularly oriented.

The atoms can therefore vibrate about certain positions. If the atoms in a lattice are held togeth electrical attractions, it can only be because some ε have lost electrons from their outer orbits and be thereby positively electrified, whilst other atoms gained electrons and become thereby negatively electr

The atoms in a solid metal may then perhaps be di into two groups, viz, those which have less tha normal number of electrons circulating round their n and those which have more. By normal number is understood the number of planetary electrons whic required just to neutralise electrically the positive c of the nucleus. We may then say that the atoms bu up a solid metal are either positive or negative ions.

When a particular electron is in orbital motion r a certain particular nucleus it may happen that certain position in its orbit the force binding it to nucleus is very small and a small additional electric

may therefore cause it to cease to circulate round that nucleus and be changed over to circulate round another adjacent nucleus. The first atom becomes a positive ion and the second a negative ion by this exchange. A similar transfer may thus again and again occur. If the impressed electric force acts always in the same direction in the metal mass, this exchange of electrons from atom to atom will always take place in the direction of that force, and there will be a progressive transfer or drift of electrons, but there will not be any free electrons in the usual sense of the term, meaning by that, electrons quite unattached and roaming about between atoms and with no permanent place of abode. Electric conduction currents may therefore consist in this atom to atom exchange of orbital electrons. When the metal is homogeneous or pure and the atomic volume small or atoms near together, and when the temperature is low or the atomic vibrations small then this electron exchange is facilitated or the electric conductivity is large.

When the atoms are a mixture of different atoms, as in an alloy, and the temperature high, then the conductivity is reduced or is small. In the case of certain materials and oxides, rise of temperature by facilitating ionisation of atoms may increase the conductivity, and in the case of selenium even the action of light increases it for the same reason.

The difficulties and objections to the theory of electric conduction, based on the assumption that there are free mobile electrons in metallic conductors roaming about in the atomic interstices, are discussed in many standard text-books, and space does not permit of a summary of them to be given here. An alternative theory has been given by Sir J. J Thomson in his book, *The Corpuscular Theory of Matter*, which meets many of the objections to the free electron theory. Thomson's theory assumes, as above explained, that there is a continual exchange of electrons between atomic ions, positive and negative. We shall, however, consider in Chapter III. some of the

facts connected with the emission of electrons from incandescent metals and carbon, which strongly suggest that there are at high temperatures free electrons in the metal which make their escape through the surface.

We can only say that at present we have no absolutely certain knowledge of the method by which electricity is transported through metallic conductors, and that arguments may be advanced both for and against all the theories of metallic conduction which have yet been proposed.

The reader desirous of more detailed information may be referred to a book on *The Quantum Theory*, by Fritz Reiche (English translation · Methuen & Co., London. Also to a treatise on *The Theory of Electrons*, by Dr. H. A. Lorentz. (David Nutt & Co , London.)

The applications of these researches on electric conduction in electrical engineering are important. We require in technology two classes of conductors, first, those which conduct as well as possible, and, secondly, materials of high resistance with a small change of resistance with temperature for resistance coils and measuring instruments. For the first requirement, soft annealed electrolytic copper produced as described in Chapter VII. supplies our requirements. If by any means we could obtain supra conductors at ordinary temperature with much less resistance than copper, we should be able to transmit large amounts of power electrically at low voltages and with conductors of small section and greatly increase the economic range of our operations.

As regards the second requirement, it is well met by such alloys as manganin and constantan, the composition of which has been given.

The volume specific resistance of manganin and its small temperature change has already been mentioned above.

Another very useful alloy is that called Nichrome III or Kromore, an alloy of 85 per cent. nickel and 15 per cent. chromium. Its specific resistance is 89 microhms per centimetre cube at 20° C. and 99 at 1,000° C.

It has the quality that, unlike iron, it can be heated to a bright red heat without being rapidly oxidised. It is therefore much used in the manufacture of electric radiators and electric fires and electric cooking appliances.*

Another, and extremely important high resistance conductor is metallic Tungsten, used for the filaments of incandescent lamps and thermionic valves.

The preparation of this element in a reguline metallic state, suitable for being drawn into wire, was a triumph of synthetic chemistry and of persistent highly skilled scientific research. Its native ores are first reduced to the state of oxide of tungsten, and this is reduced by heating in a current of hydrogen gas to a finely divided metallic state. These minute granules are welded together by heating in an electric furnace and hammering until a mass of solid metal is obtained, which can be drawn down through diamond dies into hard wire of very great fineness.

The melting point of tungsten is about 3,382° C , and its resistance in the form of metallic hard-drawn wire is 4·82 microhms per centimetre cube at 0° C., 25·70 at 727° C., 59·1 at 1,727° C., and 96·2 at 2,727° C.

The preparation of the Thoriated Tungsten, which may be described as a certain kind of alloy of tungsten and thorium, has been the outcome of scientific research, which has had an enormous influence on the progress of wireless telephony. At the same time the preparation in electric furnaces of highly refractory and infusible metals, such as molybdenum, has helped to create new electrical industries and manufactures. The outcome of pure scientific research directed to the production of insulators and conductors having required qualities, has shown us the infinite possibilities that yet remain in this field of discovery and work.

The theory of electric conduction in metals which assumes the presence in the interatomic spaces of free

* The term Nichrome covers various alloys of nickel, chromium and iron.

electrons behaving like the molecules of an occluded gas explains by the aid of a few plausible assumptions many electrical phenomena. It has been already explained that there are serious objections to it, if we hypothecate that the equipartition of energy holds good for atoms and electrons, and that the translational energy of a free electron must be the same as that of a monatomic gaseous atom. Accordingly, modifications have been proposed by several eminent physicists. The following outline of a theory is put forward in the attempt to avoid the necessity for any assumption that there are at any instant free detached electrons which share with the atoms in the heat energy.

According to present views the atom itself is a structure held together by electric forces, as the gravitational stresses between the nucleus of the atom, which contains most of the gravitational mass and the electrons, are negligible in magnitude compared with the electric stresses between the positively-charged nucleus and the negative planetary electrons.

Hence, it seems reasonable to assume that the force which holds together atoms into crystals or into masses is also electric.

This, then, implies that there must be in a solid metal two, and perhaps three, classes of atoms, viz., positive ions or atoms which have lost one or more planetary electrons, negative ions or atoms which have gained or taken up one or more extra electrons, and perhaps some neutral atoms in a non-electric state, and possibly also some detached electrons. These atomic ions must be completely intermixed.

The next assumption we may reasonably make is that there is a constant change of condition. A particular atom does not remain permanently a positive, neutral or negative ion, but it is constantly changing from one state to the other by the loss or gain of electrons.

The reasons for this may be stated as follows :—

In a solid the atoms are nearly in contact, as shown by

the measurement of atomic diameter and of the Avogadro constant for the gram-atom of metals.

Consider, then, 2 atoms in close proximity.

A particular electron *e*, revolving round one nucleus *n*, is held in its orbit by the attraction to that nucleus. When, however, that electron passes in its orbit between the 2 nuclei of 2 atoms the nuclear attractions on it are opposed and weaken each other (see Fig. 3). If, then, atom 1 has already lost an electron and become positively charged, whilst atom 2 is in a neutral condition, and if there should happen to be other similarly ionised atoms 3

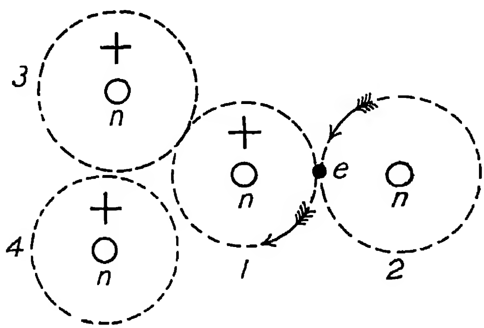

FIG. 3.

and 4 on the side of atom 1 away from atom 2, then the force on the electron *e* may be sufficient to make it leave atom 2 and jump into an orbit in atom 1; thus leaving atom 2 with one positive charge The same process may be constantly repeated everywhere throughout the mass. Hence a particular atom does not remain in a constant condition as regards ionisation, but as electrons jump into it or jump out of it into adjacent atoms it changes from a negative ion to a positive one or to a neutral one. There is, therefore, an irregularly distributed jumping of electrons from atom to atom, but no electron remains in the free state as assumed in the ordinary theory.

Suppose, then, that such a mass of metal is placed between two electrodes of a battery. In these electrodes there will be an excess or deficiency of ionised atoms of one kind. In the negative electrode an excess of negative atomic ions and in the positive electrode a deficit of the same.

It is commonly said that when an electromotive force acts on a conductor the electric force causes a unidirectional drift of the free electrons. This, however, assumes that electric force from the electrodes can penetrate into the interior of a metal mass, which is certainly not the case.

The action by which this unidirectional drift of electrons is made to take place is as follows. In that layer of the conductor next to and in contact with the negative electrode, the jump of the electrons will always take place away from the negative electrode, because the atoms of this last are mostly negative ions. Accordingly, in the atomic layer of the conductor next but one the tendency of the electron jumps will always be more away from the negative electrode than towards it.

At the positive end of the conductor the effect is the opposite. The positive electrode comprises atoms which for the most part have lost electrons and are therefore ready to take them up. Hence, in that layer of the conductor next to it, the tendency of the electron jumps is towards the electrode, and is in the same direction throughout the conductor.

In the case of a conductor not subject to electromotive force, the electron jumps from one atom from which it is flung out into another atom which has previously lost an electron. There is, therefore, a continual change in the atoms which are positively ionised by loss of electrons, but, on the whole, only a give and take of energy and no final dissipation of energy and, therefore, no change in temperature of the mass. There is only an irregularly directed jumping of electrons from atom to atom. The

process resembles the collision of elastic spheres like gas molecules, in which there is no change of temperature of the whole mass on the average.

The process of unidirectional motion of electrons. through the mass is, however, somewhat different The negative electrode then is kept continually supplied with atoms which have gained one or more electrons, and from which they are expelled again into the conductor.

When expelled they jump into atoms of the conductor which are positive ions at that moment and dissipate some of their kinetic energy in so doing. When these atoms again in turn part with an electron it can only be in the direction of the further lying atoms of the conductor. The electrons cannot come back again into the negative electrode. Hence this process, repeated from layer to layer or atom to atom of the conductor, amounts to a transmission of electrons through the mass, but at each entry of electrons into atoms some energy is dissipated by the atom having its kinetic energy increased by the impact of the electron. This dissipation is proportional to the square of the velocity of the electron, and, therefore, to the square of the current. Hence we deduce Joule's law.

We have then to notice the way in which this electronic energy is continually recuperated, so that the electrons may go forward When electrons jump out of the negative electrode into the layer of conductor atoms next to them they make this first layer of conductor atoms negative The inductive action, therefore, expels a corresponding number of electrons from the second layer of conductor atoms and leaves these last positive ions. There is, therefore, an electric force (X) between these two layers of atoms. If we call the small distance between the outer surfaces of the atoms b, then the potential difference between the surfaces of the positive and negative ionised atoms is Xb, and the energy given up when the electron impinges on the positive ion is eXb. If the total kinetic energy of the atom against which the

electron impinges is $\frac{1}{2}mv^2 = a\theta$, where θ is the absolute temperature, then we may equate eXb to a certain fraction of this atomic thermal energy, which is increased, and put $eXb = \beta\frac{1}{2}mv^2 = \gamma\theta$.

If the conductor has N atoms per centimetre cube, then there are $N^{\frac{1}{3}}$ atoms per linear centimetre and $N^{\frac{2}{3}}$ per square centimetre

If each atom discharges p times per second, then the total electricity per second passing per centimetre square across from one layer to the next is $epN^{\frac{2}{3}}$. Also, if d is the diameter of an atom $d + b$ is the atomic interval and $N^{\frac{1}{3}}(d + b) = 1$.

Hence, we can write for the current per square centimetre of cross section,

$$C = \frac{(eXb\,(d + b)\,N^{\frac{1}{3}}\,(epN^{\frac{2}{3}})}{\beta\frac{1}{2}mv^2}$$

or

$$C = \frac{e^2Xb\,(d+b)pN}{\gamma\theta}$$

If the conductor is a prism having a length l cm. and section S sq. cm., and if V is the potential difference of the electrodes, then X is nearly equal to V/l, and since b is probably small compared with d when the atoms are closely packed, we have

$$C = \frac{VS}{l}\frac{bdpe^2N}{\gamma\theta} = \text{total current.}$$

Hence the resistance of the conductor is

$$R = \gamma\frac{l}{S}\frac{\theta}{bdpe^2N}$$

That is, it is proportional to the length, to the absolute

temperature, and to a specific constant $\rho = \frac{1}{bdpe^2N}$, and inversely as the section S.

This formula is of the proper dimensions, and makes the resistance in electro-magnetic measure of the dimensions of a velocity as it should be. The formula is also nearly identical with one given by Sir Joseph Thomson in his book "The Corpuscular Theory of Matter," Chapter V., in his "second theory" of electric conduction. The difference between his fundamental postulates and those given above are that he assumes the positive and negative atomic ions to be all united in pairs, and that these doublets are first rotated by the impressed E.M.F. so as to have their axes in line and polarities in the same direction. In the case of the present theory there is not supposed to be any such rigid union between the + and − ions. Thomson, however, derives his formula by a rather stricter process of reasoning which enables him to determine the constant, and his formula in our notation is equivalent to

$$R = \frac{9}{16} \frac{a\theta}{e^2 db N p},$$

where $a\theta$ is the mean kinetic energy of a molecule at the absolute temperature θ Thomson also deduces from the same theory the conductibility for heat, and shows that the ratio of thermal to electric conductivity is constant and proportional to the absolute temperature, in other words, he deduces the Wiedemann-Franz law.

It seems clear, therefore, that the laws of electric conductivity can be deduced from the above hypothesis without any assumptions as to free mobile electrons in the metal.

The process of conduction consists, then, in electrons leaping from atom to atom in one direction, and is, therefore, facilitated when the atom is equally ready to give up and take up electrons. It is hindered by any cause which disturbs this equality.

Rise of temperature, that is increase in rate of vibration of metallic atoms, seems to facilitate giving up of electrons, but hinders taking of them up. This is shown by the fact that rise of temperature facilitates oxidation of metals. The atom of oxygen is very desirous to take up 2 more electrons in its outer orbit so as to increase them from 6 to 8, which is the stable number Metallic atoms can give up electrons and thereby become positive ions, but it is not so easy for them to take up electrons, as shown by the rather infrequent formation of metallic hydrides.

These hydrides are for the most part decomposed or destroyed by use of temperatures, as in the case of arsenic hydride. There is nothing, therefore, very improbable in the supposition that rise of temperature in metals, by decreasing the power of the atom to take up an extra electron or two, disturbs that give and take equality necessary to allow of a free motion of electrons through the mass jumping from atom to atom in contact. Hence, it reduces current for a given E.M.F. or increases resistance.

This assumption is consistent with other facts as to the great deteriorating power of certain non-metallic atoms on metallic conductivity. Phosphorus, sulphur, arsenic, and carbon readily form hydrides, thus showing their power of taking up and retaining electrons.

If, then, a few atoms of arsenic or sulphur are put into a good conducting metal, such as copper, these atoms tend to become permanently negatively charged by taking up electrons, and then, though few in number, they act like the negatively-charged grid of a thermionic valve in reducing the electron progress or electric current or, in effect, increasing the apparent electric resistance. A very small percentage of phosphorus, arsenic or sulphur enormously increases the specific resistance of copper or silver or any good metallic conductor.

In the same manner the presence of two different kinds

of metallic atoms in the form of an alloy increases specific resistance.

Thus, let a comparatively small number of zinc atoms be put into copper. The zinc atoms are more electropositive and tend to lose electrons more easily than the copper, or, what is the same thing, take up electrons less readily. Atoms of zinc then become positively charged, and, therefore, some atoms of copper must be permanently negatively charged, and the facility and equality of electron exchange is disturbed. On this theory the difference in specific resistance of various conductors is dependent upon a difference in the readiness of the atom to take up and give up electrons. If the atom is very ready to take up, but not to give up, electrons, then it is a bad conductor. Also, if it is more ready to give up than take up electrons as in the case of *hot* metals, it is a poor conductor. If there is an exact equality, as in the case of metals cooled to a low temperature, then it is a good or even a perfect conductor.

The alloys generally are worse conductors at the same temperature than most pure metals, because this equality is disturbed by the admixture of otherwise good conductors

The good conductors, then, are those which consist of one kind of atom (pure metals) close together (small atomic volume) and in which there is an equality of exchange of electrons. Lowering the temperature by bringing the atoms to rest facilitates the electron exchange, and therefore reduces resistance It is curious that those metals, lead, mercury and thallium, which become perfect conductors (supra conductors) at temperatures a little above absolute zero lie in the periodic table close to the radio-active elements, radium, thorium and uranium, which are unstable atoms and continually breaking up.

This hypothesis, then, gives in outline a theory of metallic conduction which is broadly in accord with facts, yet it evades any difficulty with regard to abnormal

atomic specific heats, because we make no assumptions as to the thermal energy being in part due to electronic kinetic energy. That thermal energy is simply due to atomic vibrational energy.

The same theory throws light on the non-conducting power of insulators. Dielectrics consist of very bulky polyatomic molecules held together by electric attractions. The molecules are mostly electrically neutral and held loosely together. Hence all insulators are brittle or fragile and with no tensile strength like metals. Even sulphur, though an element, has probably a polyatomic molecule. Hence there is no such exchange of electrons between atom and atom as in the case of metals. Dielectrics, however, gain conducting power when heated, and their conductivity *increases* with rise of temperature. It is, therefore, no doubt due to the ionised atoms in the molecule sliding over each other In other words, the conductivity of dielectrics is due to motions of ionised atoms and not to motions of electrons. Hence it is *electrolytic* in character, and since this atomic motion is facilitated by rise of temperature, dielectric conductivity increases with temperature.

The same is probably the case with the oxides of earthy metals, such as lime, magnesia, etc., the conductivity of which increases very rapidly with rise of temperature.

The true dielectric displacement in dielectrics may be due to an elastic straining or electrical displacements of the ionised atoms which build up the molecule, and the true electric conductivity to a sliding of the atoms of the molecule or to an irreversible displacement.

One theory of metallic structure appears to be that *all* the metal atoms are positive ions, having lost one or more electrons, and that these positive ions are held in a lattice by intermediate electrons, the latter being mostly a face-centred cubic lattice. Electric conduction is then supposed to take place by the electron lattice moving freely through the atomic lattice.

This theory does not explain in the least how *all* the

metal atoms become positive ions, nor why the intermediate electrons are not taken up into them again.

From some calculations it seems that on this theory the tensile strength of the metal should be millions of times greater than it really is.

CHAPTER II

FERROMAGNETISM

THE genius of Faraday as an experimental philosopher was never more markedly exhibited than in that great series of his Electrical Researches in which he discussed and described the fundamental magnetic properties of all substances and created thereby an entirely new branch of experimental science. He not only showed that all material substances are affected in some way by a magnetic field, but he introduced a novel mode of describing the observed effects with profound insight into the phenomena

He had accustomed himself to think of a magnetic field or region in which there is magnetic force, as mapped out by *lines of magnetic force.* He now advanced a stage farther by regarding various substances placed in that field as having more or less *conductivity for lines of magnetic force.*

The substances with less conductivity than air or vacuum he called *diamagnetic.* The substances with greater he named *paramagnetic*

He noted also that some substances could be magnetised so that they themselves created lines of magnetic force when in that state, and these were called *ferromagnetic.* They are few in number, and the chief examples are iron, nickel, cobalt, and their alloys.

Faraday's great generalisation, derived from numerous observations, was that a paramagnetic or ferromagnetic substance when put into a non-uniform magnetic field tends to move from weak to strong parts of the field, whereas the diamagnetic substances tend to move in the opposite direction.

The force urging a paramagnetic body in this way is proportional to the strength of the field and to its rate of change in that direction and to a coefficient called its magnetic susceptibility.

Faraday proved that this action is a relative one and is dependent upon the relative susceptibilities of the substance and its surrounding medium.

Thus a glass tube, full of a weak solution of sulphate of iron, when in air exhibits paramagnetic quality, but if the tube is suspended in a vessel containing a very concentrated solution of chloride of iron, it will exhibit diamagnetic qualities relatively to this medium.

Thus the same principle holds good which controls the floating or sinking of a solid in a liquid. It is a question of relative density, whereas in the magnetic case it is a question of relative susceptibility.

This last term was introduced into magnetic science by Lord Kelvin, who also coined the useful word, *permeability*, to replace Faraday's term, conductivity for lines of magnetic force.

A careful comparison of the phenomena connected with electric current production in an electric circuit and magnetic flux production in a magnetic circuit, made it clear in course of time that there was a close resemblance between the two cases.

The current (C) is produced in an electric circuit by an agency, called electromotive force (E M.F), and the current reckoned in amperes is proportional to the E.M.F. reckoned in volts, and to the electric conductance K of the circuit. Hence, $C = K \times$ (E M F). In the same manner the state called magnetic flux, which is reckoned as so many " lines of force " is produced in a paramagnetic or ferromagnetic substance by an agency called magnetomotive force (M M.F.).

The flux (Z) is proportioned to the M M.F. and to a quantity called the magnetic permeance (P) of the circuit. Hence $Z = P \times$ (M M.F).

If a long helix of insulated copper wire has an electric

current passed through the wire a magnetic field will be created in the interior. If a bar of iron or other ferromagnetic material is placed therein it will become magnetised and the two ends will become magnetic poles, one North, the other South. The poles are themselves the source of magnetic force which acts on the interior of the iron in a direction opposed to that due to the current in the wire. Hence it is difficult or impossible to determine the actual magneto-motive force acting on the iron.

G. Kirchhoff, in Germany, therefore suggested that it would be necessary to employ in magnetic measurements an iron ring or endless magnetic circuit, so that free magnetic poles no longer exist. If an iron ring having a cross section S in square centimetres and a mean perimeter l cm. is uniformly wound over with N turns of insulated wire, and if a current of A amperes is passed through the wire, then a magneto-motive force is created, which produces a magnetic flux (Z) in the iron. The permeance P of the magnetic circuit is proportional to the section (A) and to the permeability (μ) and inversely as the length (l) of the magnetic circuit. If B is the flux density or lines of force per square centimetre of cross section, then $BS = Z$ and $P = \mu S/l$, and the magneto-motive force M.M.F. $= l \times H$, where H is the magnetic force in the interior of the iron. Accordingly, we have $B = \mu H$. The magnetic force H can be shown to be very nearly equal to one and a quarter times the product AN/l or ampere-turns per unit of length of the circuit.

If the ring coil is wound over with a second coil of insulated wire of N_2 turns and resistance R ohms, and if this coil is connected to an instrument, called a ballistic galvanometer, which enables us to measure the quantity of electricity sent through it when the direction of the magnetic flux in the ring is reversed, then it can be proved that $B = RQ/SN_2$.

We have, then, all the necessary means of measuring both B and H and therefore the ratio B/H which is the permeability μ. We can then set out in the form of a

curve the values of B corresponding to various values of H and the values of μ corresponding to various values of B.

When this is done we obtain two curves, the first called a *magnetisation curve* and the second a *permeability* μ (dotted) curve, for that particular sample of iron or steel of which the ring is made (see Fig. 4). In the last quarter of the nineteenth century a very large amount of scientific work was done by various workers on this subject, such as Rowland, Bosanquet, Shelford Bidwell, J. Hopkinson and Ewing, in studying the magnetic qualities of various kinds

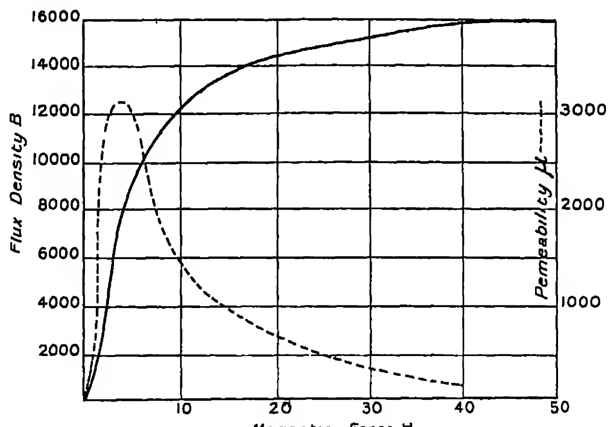

FIG 4.—Magnetisation curve (firm line) and permeability curve (dotted line) for a sample of soft annealed iron.

of iron and steel. It was then seen that in one respect the magnetic permeability differs strikingly from the electric conductivity of a material. The last named is independent of the current flowing, provided temperature is kept constant; but the first depends on the flux density and rises to a maximum value corresponding to a certain value of B.

Sir Alfred Ewing studied particularly the form of these magnetisation covers when the magnetic force is taken round a cycle of operations beginning at zero, rising to a maximum in one direction, then reduced again to zero,

taken in an opposite direction to an equal value and finally brought back again to zero. It was then seen that the magnetisation curve is a closed loop of peculiar shape (see Fig. 5). At each stage the flux density (B) lags behind the magnetic force (H) proper to it. Ewing suggested the term *hysteresis* to express this fact, and called these cyclical curves hysteresis loops. He showed that the area of the loop is a measure of the work done in carrying a unit of volume of the iron through one complete magnetic cycle. All this purely scientific work proved later on to be of immense practical importance. If, for instance, we have to construct an electromagnet, we wind on a bar of iron a number of turns of insulated wire and send an electric current through the wire. The iron then becomes temporarily magnetised.

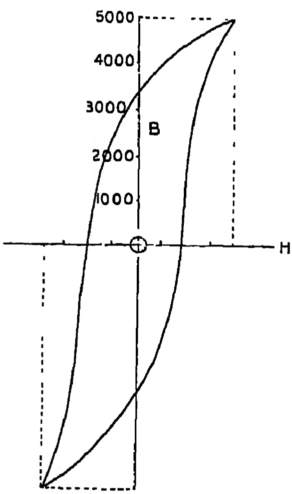

FIG. 5.—Hysteresis loop for soft iron.

In this case we require a kind of iron, in which the flux density or magnetisation is as large as possible for a given magnetic force In other words, we require a material with high magnetic permeability.

If, on the other hand, we are constructing an alternating current transformer or magnet in which cyclically varying electric currents are used, we require a material with as small hysteresis as possible Furthermore, a third requirement has to be met. If we desire to make a permanent steel magnet we have to magnetise it by applying a magnetic force, but when the force is removed we wish the steel to retain as high a magnetisation as possible and, moreover, to retain it strongly so that it is not easily demagnetised by shocks or blows.

The measure of this last quality is the reverse magnetic

force, which must be applied to bring the material back to a zero magnetic state.

J. Hopkinson suggested the term, *coercive force*, for the reverse magnetic force which was required to bring the magnetised material back to an unmagnetised state

The quality in virtue of which coercive force is required has been called by Mr. S. Evershed the *potency* of the material. A more suggestive term would, perhaps be, *magnetic stiffness* or rigidity.

Thus, pure soft iron when placed in a magnetic field retains a large percentage of its magnetisation when the field is removed, but a very small reverse magnetic force, or even a blow, destroys its magnetisation. Hence it is said to have large retentivity but small magnetic stiffness, because it requires only a small coercive force to annul its magnetisation. On the other hand, hard steel has large magnetic stiffness. As soon as dynamo machines began to be constructed in large numbers, after the invention of the Gramme ring armature winding in 1870, and the drum winding a little later, and especially after the completed invention of the incandescent electric lamp in 1879–80, a demand arose for iron of high permeability for dynamo field magnets.

Again, after 1890, when the invention of the alternating current transformer made a supply of sheet steel of small hysteretic quality necessary, iron and steel manufacturers were able by special research to meet these requirements.

In 1892 the author made an extensive study of the energy losses in the iron cores of alternating current transformers by various makers, and found them to be much larger than was generally assumed. In short, the sheet-iron then obtainable had large hysteresis energy losses in it. Here again research supplied the required material. As far back as 1882, Sir Robert Hadfield, one of our most eminent metallurgists, had prepared steels containing a small percentage of silicon.

It was found later on that silicon steels, having about 3·5 to 4 per cent. of silicon with low carbon content, give

a material which has far less hysteresis loss than ordinary steel. For commercial purposes it is usual to reckon the hysteresis in watts per pound weight of the laminated steel taken at a frequency of alternation of 50 and a maximum flux density of 10,000 lines per square centimetre, the sheets being 0·014 in. thick.

The energy loss in the steel is, however, only partly due to hysteresis, but in part to eddy electric currents set up in the steel.

In good charcoal iron the total loss is 1·2 watts per pound in the above units. For mild steel it is 1·09, but for silicon steel it is 0·44.

Moreover, the total loss in the iron is 67 per cent. hysteresis and 33 per cent. eddy current loss, but in the silicon steel it is 75 per cent. hysteresis, and only 25 per cent. eddy current loss. The reason for this difference is the lower electric conductivity of the silicon steel, which tends to reduce eddy current loss.

Silicon steel is now prepared and sold in sheets for transformer core making under various trade names, such as "Stalloy" and "Lohys."

The introduction of this material as a result of scientific research has effected an enormous economy in the total cost of the electric energy dissipation of the cores of the tens of thousands of transformers now in use, probably many millions sterling. Another direction in which scientific research has immensely assisted technology is in the discovery of types of steel having large magnetic stiffness, large coercive force and high retentivity for the manufacture of permanent magnets

It was found in the quite early days of magnetic research that glass-hard steel, made by quenching red hot carbon steel in cold water, had a vastly greater magnetic stiffness or rigidity than soft iron, and when magnetised retained that magnetism strongly. Nevertheless, permanent steel magnets deteriorated in strength with time. When it became necessary to employ permanent steel magnets in electric measuring instruments, such as moving

coil ammeters, voltmeters, and meggers for measuring electric insulation, the accuracy of the scale reading depended entirely upon the permanent magnet in it, retaining its magnetisation without loss due to the self-demagnetising force of free magnetic poles or to shocks or vibration. Hence a search began for suitable types of steel having this necessary permanence in magnetisation. Varieties of tungsten, cobalt and chromium steels have been discovered which possess this required magnetic stiffness.

A little information may first be given on the result of metallurgical research into the constitution of iron and steels.

The element we call iron is capable of existing in four allotropic forms, called respectively Alpha, Beta, Gamma, and Delta Iron. Some elementary substances are capable of presenting themselves in two or more states in which, though chemically identical, they have quite different physical properties. Thus phosphorus can exist as a yellow waxy solid, very inflammable, very poisonous, soluble in bisulphide of carbon, and easily melted. It can also exist as a red-brown powder, not poisonous, not soluble in bisulphide of carbon, and not easily melted. The waxy phosphorus is converted into red phosphorus by slow heating in an atmosphere of carbon dioxide gas

Iron also exists in several allotropic forms at various temperatures. Pure iron melts at 1,520° C., and as soon as it solidifies on cooling below this temperature and down to 1,420° it exists in the condition called delta-iron, in which it is a paramagnetic substance. If cooled below 1,420° and down to 898° C. it is in a condition called gamma-iron, in which it is more feebly paramagnetic Between 898° and 767° it changes into beta-iron and is still paramagnetic Below 767° C it passes into alpha-iron and is then strongly ferromagnetic These changes occur in reverse order on heating up again

Alpha to beta at 767°; beta to gamma at 910°.

If carbon is added, say 0·4 per cent., the change from alpha to gamma takes place at 767° C., and the beta state vanishes.

If 0·8 per cent. of carbon is added forming steel, then all the transition points lie together at 695° C., and we are left only with ferromagnetic and paramagnetic states. If manganese is added, the change temperature is still lower and is irreversible.

It will be seen that the two principal states are the alpha-iron state, when the iron is ferromagnetic, and the gamma state when it is red hot and non-magnetic or feebly paramagnetic. The iron has different specific heats in these various states, viz., 0·1055 in the alpha state, and 0·1448 in the gamma state, and also different electric conductances. In fact, alpha-iron is physically quite a different material from gamma-iron, yet chemically they are the same substance. There must therefore be some re-arrangement of the electron orbits and number of electrons in the orbits. The atomic number of iron is 26, which implies that there are 26 orbital electrons arranged in groups, possibly 2 in the innermost or K orbit; 2, 2, and 4, in the L orbit, 2, 2, 4, 2 (4, 2) in the M orbit. The 4 and 2 in brackets being valency electrons, which are more easily detached than the rest.

The essential fact about the magnetic state is that it consists in the colineation or setting in the same direction of certain elements, which are themselves essentially and always magnetic. This is proved by the fact that there is a limit to the magnetisation beyond which it cannot be increased. Also, if we break up a permanent magnet into fragments, each little fragment is itself a magnet with two opposite poles and a magnetic axis.

Ampère originated an important idea when he suggested that the magnetic element, which he took to be the atom, might owe its magnetism to an electric current circulating round it, since the magnetic field of such a current is the same as that of a thin circular disc of iron magnetised normally to its surfaces. There was, however,

no physical basis for Ampère's suggestion until the discovery of the electronic orbits in atoms.

An electron circulating in a circular or elliptic orbit is, in fact, an electric current, and the Amperian atomic currents are the electrons in revolution round the nucleus.

The question, however, arises, What are the magnetic elements which are set facing more or less in the same direction when we magnetise a bar of ferromagnetic material ?

These elements have been called Weber elements, from the physicist, W. Weber, who discussed this matter.

We ask, then, Is it the atom, or the molecule, or some aggregate of molecules forming a small crystal which is the Weber element in a ferromagnetic substance ? or is it some internal portion of the atom, such as the plane of electron orbits which is displaced ?

It seems very unlikely that in an extremely tough rigid material like glass-hard steel there can be any turning round or displacement of component crystals, however small, or even groups of atoms.

Sir Alfred Ewing, to whom we owe a great deal of valuable magnetic research, has given reasons for supposing that the displaceable element is some portion of the atoms and not the atoms as a whole.*

It may even be the nucleus of the atom which is oriented or colineated by the impressed magnetic field. This nucleus consists of protons and electrons, and these may be in rapid orbital motion so that there is produced not merely an electrostatic field, but also a magnetic field with a symmetrical form with respect to some axis.

It is a striking fact that only certain groups of three closely allied elements are predominantly ferro- or paramagnetic The whole of the 90 or more elementary substances can be arranged in order of their atomic number and in 8 columns, thus forming the periodic

* See *Proceedings of the Royal Society of Edinburgh*, Vol. 42, p 97 1921–22 Sir Alfred Ewing, F R S, on "Models of Ferromagnetic Induction"

series. The eighth column contains not only the non-valent elements—Helium, Argon, Neon, Krypton and Xenon, but also three magnetic triplets: (1) Iron, Cobalt, Nickel; (2) Ruthenium, Rhodium, Palladium, (3) Osmium, Iridium, Platinum.

Furthermore, there is a group of rare metals, the oxides of which are called the "rare earths," amongst which Praseodymium, Neodymium, Ytterbium, Samarium, Gadolinium and Erbium, are markedly paramagnetic or even ferromagnetic. Some authorities consider that if Erbium could be obtained in a metallic state in a solid form it would have even stronger ferromagnetic properties than iron. The erbium oxide, Er_2O_3, is four times more paramagnetic than the corresponding oxide of iron.

We have not yet been able to discover what is the particular structure in these elements which produces the ferromagnetic qualities, and the difficulty of the problem is increased by the discovery of certain compounds or alloys of metals, which individually do not possess any or very strong paramagnetic power and yet make a ferromagnetic material when alloyed. Thus the alloy called Heusler's alloy is a mixture of 10 per cent. aluminium, 20 per cent. manganese, and 70 per cent. copper. The copper and aluminium by themselves are diamagnetic metals whilst pure manganese is paramagnetic, but the alloy is ferromagnetic, exhibits magnetic hysteresis, and has magnetic qualities strongly resembling those of nickel or poor cast-iron Heusler considers that the essential magnetic ingredient is an alloy having the chemical formula, $Al(MnCu)_3$, one atom of aluminium being associated with three of manganese and three of copper. It is significant that the diamagnetic element, copper with atomic number 29, yet stands in the periodic series in close conjunction with the ferromagnetic elements, iron, cobalt and nickel, with atomic numbers, 26, 27, 28. In the same way silver and gold stand in close contiguity to the palladium and platinum triplets. Although research has not yet given us a clue to the inner

meaning of these facts, it has yet given us important guidance as to the best materials to use for making permanent magnets.

In this connection we must refer again for a moment to the chemistry of iron. Pure iron in the alpha condition is called by metallurgists *ferrite*. It is soft and strongly ferromagnetic. It has great retentivity for magnetism but small magnetic stiffness. Hence small coercive force is required to deprive it of residual magnetism. Iron combines at a high temperature with carbon to form a carbide of iron, Fe_3C, called *cementite*. Cementite dissolves in very hot or molten iron, but more freely in gamma-iron than in alpha-iron. Suppose we put into molten iron just enough carbon to form that amount of carbide of iron which the delta-iron can dissolve and then let the iron cool slowly, it will pass back through the gamma and beta states to the alpha condition. But the alpha-iron cannot hold as much carbide, and hence the excess of carbide crystallises out in layers. A material called *Pearlite* is then formed of alternate layers of ferrite and cementite. It is a variety of soft carbon steel.

If, however, we cool the iron quickly the carbide has not time to separate out, but is gripped and held in a uniformly diffused solid state. This produces a hard carbon steel. The solid solution of carbon in gamma-iron is called austenite, but it passes back into martensite as the iron changes into the alpha state

The special magnetic property of the solid solution of ferric carbide or cementite in ferrite when the carbide is diffused, is that it prevents the magnetic elements, whatever they are, atoms, molecules, or internal parts of atoms, becoming disarranged again when once their axes have been colineated or set in the same direction by a magnetic field. Accordingly, hard carbon steel has great magnetic stiffness, and this is measured by the large coercive force or reverse magnetic force which has to be applied to the magnetised material to remove all its

remanent magnetism. Now it has been found that the metal tungsten (chemical symbol = W) can also form a carbide, viz., WC, and this has even greater power than the ferric carbide, Fe_3C, of bestowing magnetic stiffness on steel. The best result is obtained when the tungsten is about 6 per cent. of the iron, and when ferric carbide is present as well. Mr. S. Evershed gives as the best composition for permanent steel magnets a tungsten-carbon steel containing 6 per cent. of tungsten, 0·72 per cent. of carbon and the rest iron. This corresponds to a mixture of a million atoms of iron with 39,000 molecules of tungsten carbide and 39,000 molecules of ferric carbide. For this material the coercive force may rise to 60 or 85 c.g.s. units or more. Research has discovered other alloys of as great or greater magnetic stiffness, very suitable for making permanent magnets. These are :—

(1) Chrome steel = 2 per cent. Cr, 1 per cent. C, 97 per cent. Fe.

(2) Tungsten steel = 5·5 per cent. W, 0·55 to 0·8 per cent. C.

(3) Low and medium cobalt steel = 6 per cent. and upwards of Co.

(4) Cobalt-chromium steel = 9 to 20 per cent. Co, 9 per cent. Cr, 0·8 to 1·0 per cent. C.

(5) High cobalt steel = 35 per cent. Co, 65 per cent. Fe = Fe_2Co.

These materials store up the following amounts of energy in magnetic form per centimetre cube :—

Chromium-carbon steel . .	9,200 ergs.
Tungsten-carbon steel . .	10,400 ,,
Cobalt-chromium, 9 per cent. Co. .	19,900 ,,
,, ,, 12 ,, .	23,000 ,,
,, ,, 15 ,, .	25,000 ,,
,, ,, 35 ,,	31,800 ,,

The tungsten-carbon steel is most usually employed in Great Britain for making the permanent steel magnets of

constant strength required in direct current ammeters, voltmeters, galvanometers, meggers and house meters. The chromium-carbon steel is largely employed in the United States. These materials provide the electrical engineer with the instruments necessary for accurate measurement in electrical technology.

Further, research has shown us how to produce qualities of iron almost destitute of ferromagnetic power.

The element, manganese, when alloyed with iron has the peculiar power of reducing magnetic permeability.

Thus, Sir Robert Hadfield long ago produced his manganese steel of composition : manganese, 12 per cent.; iron, 88 per cent. In addition to being very hard and possessing other valuable mechanical qualities, the magnetic permeability of this alloy is only 1·3.

Messrs. Dawson and Ferranti have produced a kind of non-magnetic iron which can be cast, the composition of which is : manganese, 6 per cent.; nickel, 9 per cent.; iron, 81 per cent. This is called *Nonmag* iron, and is used for making bed-plates of dynamos and other things which must have mechanical strength but be non-magnetic. Its permeability is also 1·3.

Some very extraordinary facts have been discovered with regard to nickel-iron alloys, which have provided the electrical engineer with remarkable materials. Dr. J. Hopkinson found, years ago, that an alloy of 25 per cent. nickel and 75 per cent. iron could exist in two states, either magnetic or non-magnetic, according to its previous heat treatment.

More astonishing still is the alloy of 78·5 per cent. nickel and 21·5 per cent. iron, called Permalloy. This was produced in the United States by the research chemists of the Western Electric Company, with the object of finding a material which has higher magnetic permeability for low magnetic forces than iron. It will be shown in Chapter V. that a study of the problem of the propagation of electric currents in telephone and telegraph cables had shown that a great advantage is secured if we can

increase the quality of the cable, called its inductance, and this can be done if we surround the copper conductor with a thin layer of magnetic material The magnetic force of the electric currents is very feeble The initial magnetic permeability of iron is not greater than about 100 for very small magnetic force. If we wind over the copper wire with a thin layer of iron wire we can at most increase the inductance per mile from about 1 millihenry to 10 millihenrys, but this is not enough. A deliberate research was therefore undertaken to find a material which had a much higher magnetic permeability than iron.

This has been found in the above-mentioned permalloy when subjected to a particular heat-treatment. Under a magnetising force of only 0·05 c.g.s. unit, which is about one-quarter of the earth's horizontal magnetic force, the permeability of permalloy may reach 87,000 to 100,000, which is 1,000 times greater than that of iron under the same conditions (see Fig. 6).

We have in the next place to notice the way in which the magnetic knowledge gathered by research has been applied to the solution of industrial problems in electrical engineering.

As soon as dynamo machines began to be made in large numbers, especially after the completed invention of the incandescent electric lamp in 1882, it was necessary to be able to design them to a specification. This necessitated some means of predetermining the ampere-turns or product of the current, and number of turns of insulated wire to be put upon the field magnets.

The magnetic circuit of a dynamo or the path of the magnetic flux in the field magnets lies partly in the iron cores of the field magnets, partly on the laminated steel core of the armature and partly across the air gaps between field pole pieces and armature core. We can determine from the desired electromotive force of the machine and from data given by experience the total magnetic flux. We can calculate for each part of the magnetic circuit its reluctivity, which is the quantity

$l/\mu S$, where l is the length of that part of the circuit, S its section and μ its permeability corresponding to the flux density required. The required ampere-turns to be put on the field magnet cores is given by 0·8 multiplied by the total flux Z, and by the sum of the reluctances of each part of the circuit where 0·8 is nearly equal to $10/4\pi$.

An important Paper, published by Drs. John and

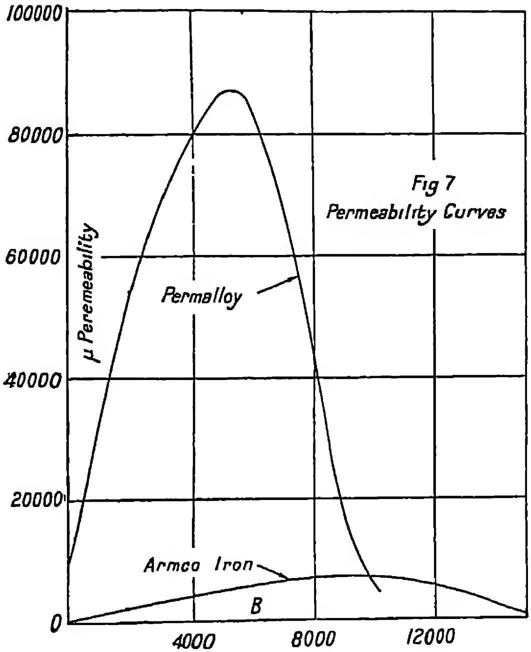

FIG 6.—Permeability curves of permalloy and of soft pure iron

Edward Hopkinson in 1886, gave valuable scientific guid ance in this manner of dynamo design. In the early days of electric lighting dynamo design was a matter of guess-work or rule of thumb, and the result was inefficiency. Thus, in the early dynamos designed by Edison for incandescent lighting, the field magnets were made with long, thin iron legs, and several of them in parallel on a

single pair of pole pieces. All this was theoretically quite erroneous, and by bringing to bear on the subject a scientific knowledge, Dr. John Hopkinson designed the Edison-Hopkinson dynamo, and made it an efficient engineering appliance.

The scientific principles of electromagnet design having been thus established by the researches of a number of investigators, and the early types of electromagnet invented by William Sturgeon and Joseph Henry having been improved by J P. Joule, the path was opened for further advances by the application of the principle that to gain great field strength or lifting power the magnetic force or ampere-turns per centimetre of length and the permeability corresponding to that force must both be as large as possible. The application of correct principles has enabled electromagnets to be made as workshop appliances capable of lifting a ton or more in weight.

Also it has enabled very powerful electromagnets for physical laboratories to be made, with which important discoveries, such as that of Zeeman, viz., the multiplication of the spectral lines by a very strong magnetic field, have been made.

These depend not only on the correct proportioning of the form of the iron core, but on the provision of an iron of extremely high permeability under large magnetic forces which the metallurgist has been able to furnish.

We may then describe, as another illustration of the dependence of electrical engineering on pure scientific research, the practical outcome of the study made of the alternating current electromagnet. About 1883 attention began to be turned to the study of alternating electric current effects.

One of the most interesting of these is that known as electromagnetic repulsion. In 1885 the author of this book suspended a small circular disc of copper in the interior of a coil of wire, the disc being hung by a thread with its plane vertical and at 45 degrees to the horizontal axis of the coil. When an alternating current of electri-

city was passed through the coil the disc turned so as to place its plane more in the direction of the axis of the coil.

In 1887 this experiment was shown to the Physical Society and at a Royal Society soirée.

Remarkable effects due to the same cause were about the same time discovered by Professor Elihu Thomson, in the United States, and exhibited by him at the Paris Electrical Exhibition, in 1889, and by the author to the Royal Society of Arts, in May, 1890, and at the Royal Institution of Great Britain in 1891. The principal experiment was called the "jumping ring." An electromagnet was made with a core, composed of a bundle of iron wires over-wound with layers of insulated wire. Through this wire could be passed a strong alternating electric current. The magnet had a shelf on it on which was laid a copper or aluminium ring. On switching on the current the ring was propelled up into the air to a considerable height.

Plates of copper placed over the pole of this alternating magnet were also powerfully repelled. The explanation of this effect is as follows :—

The magnetic field of the magnet is an alternating field or one rapidly reversed in direction. If a plate or ring of a good conductor is placed in this field powerful induced electric currents are created in it. The fluctuating field penetrating through the ring or disc creates in it an electromotive force which is in phase displaced 90° from that of the field. In other words, the E M.F. comes to its maximum at the instant when the field is passing its zero value, and *vice versâ*. This E.M.F. creates an induced current in the ring or disc. This circuit, however, possesses a quality called inductance, in virtue of which there is a delay or lag in time in the production of this induced current, and the result is that the direction of the induced secondary current is always nearly in the opposite direction to that in the magnetising coils of the magnet. Now, electric currents in opposite directions in two neighbouring conductors create repulsion between the conductors, and

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hence the ring or disc is repelled from the alternating magnetic pole. The same effect is produced in a different way if a circular disc of copper has a pivot at the centre so that it is supported in a horizontal plane and can turn about this pivot. If the disc is held near the pole of the alternating current magnet the disc is soon set in rapid rotation by the alternating eddy currents produced in it.

These and many other similar experiments were shown by the author in a Friday Evening Discourse at the Royal Institution, London, in 1891.

Very soon after they were applied in electrical technology in two very practical inventions—an alternating current electric motor and an electric house meter.

The motor, invented by Professor Elihu Thomson, is called a repulsion motor. In it coils of wire, called the rotor, are fixed to a shaft and surrounded by a magnetic field, produced by other coils or wire, called the stator. The rotor coils are perforated by the magnetic flux of the stator and repelled. Each coil in turn is short circuited or closed by means of a commutator, and when it is moved forward by the repulsive force its place is taken by another coil. These repulsion motors have, however, now been replaced in alternating current work by a type called a compensated series motor. The electric house meter depending upon the repulsion principle is still in use. A circular disc of copper is pivoted on a freely revolving axis, and the latter is geared to a counting mechanism with dials like a gas meter The copper plate revolves between the poles of a fixed permanent steel magnet, and this creates induced currents in the disc, in such a direction as to resist the motion of the disc.

There are other coils of wire in proximity to the copper disc through which the alternating current to be metered flows. For the reasons just given the induced currents in the disc cause the disc to be repelled or set in rotation away from these fixed coils.

The disc is then increased in speed until the retardation produced by the field of the fixed magnet, the resistance

due to which is proportional to the speed of revolution, just balances the acceleration due to the action of the alternating current coils. The constant speed of the disc is then proportional to the alternating current, or the number of revolutions of the disc as recorded by the counter is proportional to the quantity of electricity which has flowed through the alternating current coils. In this way the quantity of electricity supplied to a house in the form of alternating current can be measured for charging purposes

This very practical device is entirely the outcome of pure scientific work on the phenomena of electromagnetic repulsion.

Another instance of the manner in which curious and out-of-the-way electrical effects noted by experimental physicists may suddenly come to have very great industrial importance is in the application of hysteretic repulsion, discovered and applied by Mr. W. M. Mordey, of late years.

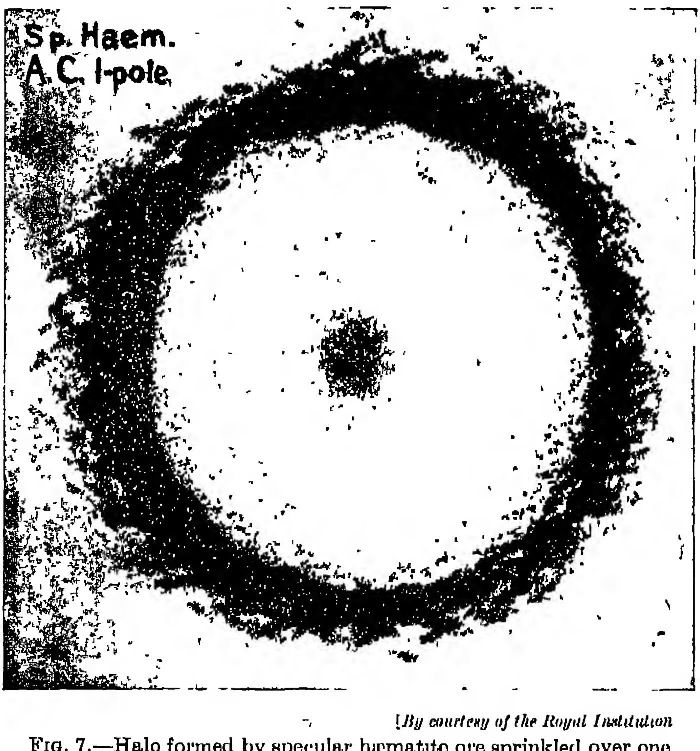
If we construct the iron core of an electromagnet of a bundle of iron wires, which are each painted or varnished to insulate them, and wind over the bundle a helix of insulated wire through which an alternating current of electricity can be sent, we have a bar magnet of which either end is alternately a North and a South pole changing, say, 50 or 100 times a second

From the pole of every magnet an influence is sent out in all directions along certain lines, which are called lines of magnetic force. We can render the path or form of these lines visible by sprinkling iron filings upon a glass plate placed over the pole.

If we use either a direct or alternating current magnet, and place a glass plate, sprinkled with iron filings, over the pole, we find in both cases that the lines of force radiate outwards from the pole, and the iron filings arrange themselves along these lines and collect together in tufts over the pole, particularly along the edges of the iron core.

The same effects are produced with filings of nickel or cobalt, or any ferromagnetic material.

If in place of these metals we use powdered specular hæmatite, which is a crystalline oxide of iron (Fe_2O_3) and is a paramagnetic body, we find that it is scarcely attracted



[By courtesy of the Royal Institution

FIG. 7.—Halo formed by specular hæmatite ore sprinkled over one pole of an alternating-current bar magnet, single phase

by the direct current magnet, but if it be sprinkled on a glass plate held over the pole of the alternating current magnet, Mr. Mordey discovered that it was repelled by the pole and the powder arranged itself in a halo or circle about the pole as if it wished to get as far away as possible. This repulsive effect seems to be increased in some cases if the magnetic force is weakened (see Fig. 7).

In a lecture given at the Royal Institution in May, 1923, Mr. Mordey showed a number of very interesting experiments with alternating-current electromagnets, single pole and multiple pole, and such powders as above mentioned These repulsive effects, he showed, are well marked in the case of iron pyrites, which is a sulphide of

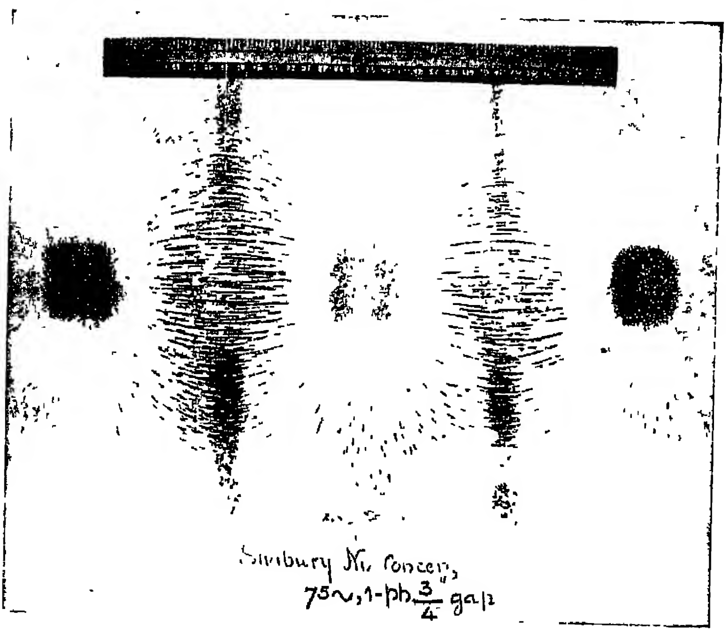


FIG. 8 —Sudbury nickel ore attracted to poles of a strong multipolar alternating current magnet

iron, and in chalcopyrite, which is a double sulphide of iron and copper.

It should, however, be noticed that there is evidently a dual action at work, both attraction and repulsion. This is well marked in the case of the minerals Pyrrhotite Fe_7S_8 and Chalcopyrite $CuFeS_2$, which are found in Sudbury nickel ore If this mineral in powder is placed over a strong alternating electromagnet it is drawn towards the poles and collects on them, but if the field is weakened

it collects in the equatorial lines owing to repulsion predominating (see Fig. 8).

In some of his experiments Mr. Mordey employed a number of alternating current electromagnets set in a row, calling these magnets Nos. 1, 2, 3, etc. All the odd numbers 1, 3, 5, etc, were excited with the same alternating electric current, and Nos. 2, 4, 6, etc., with another alternating current, differing in phase from the first by

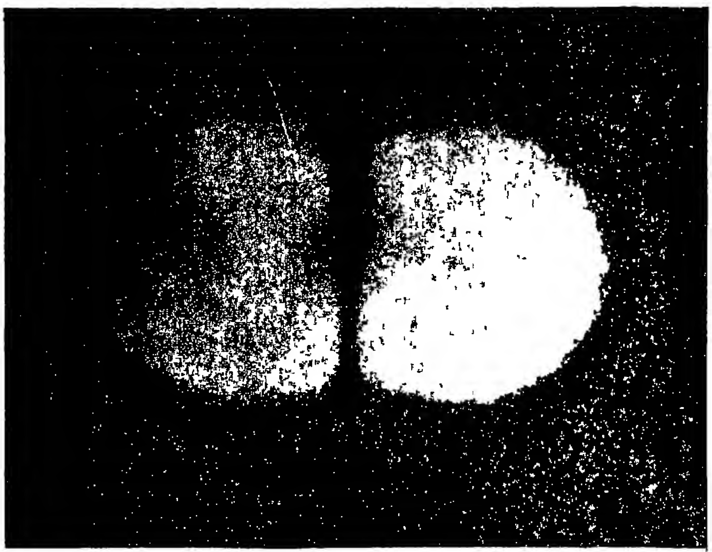
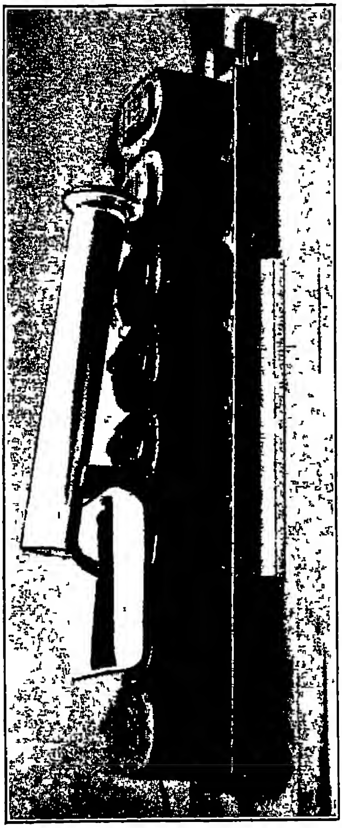


FIG 9.—Specular hæmatite halos over a horseshoe alternating current magnet, single-phase.

90 degrees; this means that one current is at its maximum value when the other current is zero. The result is to propagate along the row of magnets a so-called wave of magnetism. Placing a glass plate over the poles and sprinkling on it some of the sulphide powder, Mr. Mordey showed that the powder was forced outwards away from the poles and some of it forced along the line of poles by an evident repulsive force

A curious modification of this experiment was as follows:

Pulverised Sudbury nickel ore in powder was placed with water in a long cylindric glass vessel, which was supported in an inclined position over the multiple magnetic poles. On starting the current both water and powder were forced out of the vessel by the repulsive force in such direction that the water flowed uphill. The magnetic drag is exerted only on the susceptible portion of the ore, mostly pyrrhotite, but the friction between it and the water carries the latter along and empties it out of the inclined tube (see Fig. 10).



[*By courtesy of the Royal Institution*

FIG 10.—Water flowing uphill, carried by the repulsive effect on Sudbury Nickel ore of a series of alternating current electromagnets of alternate polarity.

Another very strange effect with powdered loadstone (magnetic oxide of iron) was discovered by Mr. Mordey in connection with the above-described two-phase multiple pole magnet.

In this case the powder, when placed on a glass plate over the poles, builds itself up into fin-like planes, which are formed by adherent particles, but which are evidently repelled by the magnet as the planes grow in height by the repulsion of each particle by the magnetic poles and by the forward propelling action due to the advancing magnetic field

which results from the use of a two-phase electric current as above described (see Fig. 11).

In all these experiments we are clearly concerned with two kinds of action on each particle, viz., an attractive

FIG 11 —Powdered loadstone forming fin-like planes of force when placed on a plate over a multiphase alternating-current magnet.

and also a repulsive force, and the repulsive force appears to become weaker when the field becomes stronger in some cases. In the lecture above mentioned, Mr. Mordey discussed the various causes to which the above effects may be due, and he came to the conclusion with which the

author of this book agrees, that the effective source of this repulsion is magnetic hysteresis. In the first place he dismisses the suggestion that it is due to normal electromagnetic repulsion, the nature of which has already been explained. This electromagnetic repulsion can only take place with metal rings or masses of a certain size and of good conductivity. Mr. Mordey showed, however, that the repulsive effect observed by him in the case of these feebly magnetic powders does not take place when finely powdered aluminium metal is placed on a glass plate over the pole of an alternating-current electromagnet. Hence the repulsion in the case of the magnetic powders must arise from a different cause to that in the case of masses of good conducting metals.

That it is due to magnetic hysteresis in the former case may be proved in the following way:—

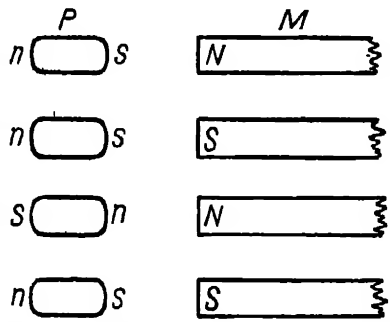


FIG 12.—Diagram illustrating the effect of magnetic hysteresis in producing the Mordey repulsion

Let us suppose that M represents an alternating current electromagnet and that the successive changes in magnetic polarity, which take place, say, 100 times a second, are represented by the diagram M denoting changes in time and not in space of the polarity of this magnet (see Fig. 12). Let P be a little particle of some material like specular hæmatite or iron ore, which has a large magnetic hysteresis This means that changes in its magnetisation lags behind changes in applied magnetic force. Suppose the pole of the magnet M is, say, north (N), it will induce in the particle a south (S) pole at the end nearest and north (N) pole at the remote end But since *s* is nearer to N than *n*, on the whole the effect on the particle will be a feeble attraction. If, then, the pole

changes to south (S), and if there were no hysteresis in the particle, it would simultaneously change its poles to n and s, and as the n is nearer to the S than the s, the result would still be feeble attraction. In other words, in the absence of magnetic hysteresis in the feebly paramagnetic particles, the effect of a strong alternating current electromagnet on them would be to cause an attraction of the particles to the pole. Let us next consider what would happen in the case when the particles have large magnetic hysteresis.

In this case when the magnet pole changes from N to S the end of the particle nearest to it still remains a south pole (s) and only changes to a north pole (n) after a small interval of time (see second row of the diagram in Fig. 12). But by that time the magnet pole has changed back to north (N), and a little consideration will show that with sufficient hysteresis the induced pole in the particle nearest to the magnet pole will be always of a similar polarity. Hence there must be on the whole a resultant feeble repulsion of the particle.

In several of Mr. Mordey's experiments there was evidence that this repulsion was decreased by increasing the maximum value of the cyclical magnetic force acting on the particle. This is probably explained as follows: We have shown in the above paragraph that this repulsive force arises because, when the inducing magnetic pole changes, say, from N to S, the pole s induced in the end of the particle nearest to the pole remains s whilst the magnetic pole becomes S, and that when s changes to n in the particle, by that time the magnetic pole of M has changed to N. Hence the end of the particle nearest to the inducing magnetic pole is always of a similar polarity. But now, if the inducing pole is very strong it will tend to create more quickly a pole of opposite sign in the end of the particle nearest to it, and the resultant repulsion will be reduced even if not changed to an attraction.

Hence this repulsive effect discovered by Mr. Mordey depends not merely upon the particles of the powder consisting of a material with large magnetic hysteresis, but

upon the magnetic force exerted upon them not being too strong. The particles possess ferromagnetic permeability, in virtue of which they tend to move from weak to strong places in the magnetic field. But they also possess magnetic hysteresis, and in consequence of this there is a dissipation of energy. The particle, therefore, tries to move from strong to weak places in the field to make this dissipation a minimum, and its actual position depends on the relative magnitude of these two forces.

This peculiar repulsive effect, which may be called the "Mordey effect," does not exhibit itself in the case of particles of pure iron or of steel, such as that called "stalloy," with relatively small magnetic hysteresis

The proof that this effect is not due to simple electromagnetic repulsion is that it does not take place with good conducting powders, such as aluminium or copper filings. On the other hand, direct measurement has shown that materials which in the powdered state are repelled have all very high magnetic hysteresis. In fact, specular hæmatite has more than 500 times the hysteresis loss in the silicon steel called stalloy.

The energy loss due to hysteresis can be expressed by a formula of the form $W = hB^{1 \cdot 6}$, where B is the maximum flux density in the sample during the magnetic cycle and h is the so-called hysteretic constant The hysteretic constants as given by Mr. Mordey for a number of substances, are as follows * —

Stalloy (silicon steel) .	0·00076
Nickel . . .	0·001 to 0·0012
Cobalt . . .	0·012
Grey Cast Iron	0·013
Magnetite or magnetic oxide of iron	0·0235
Hardened carbon steel . .	0·025
Specular Hæmatite . .	535 times stalloy.

It is clear that the substances which in powder show

* See W M Mordey on "Some New Effects of Alternating Magnetism" *Proceedings of the Royal Institution of Great Britain*, Vol 24, Part I Friday Evening Discourse, May 18th, 1923

Fig 13.—Mordey mineral separator.

this peculiar repulsive effect have all large magnetic hysteresis.

Mr Mordey has, however, gone a step beyond a purely scientific investigation of the effect, and made a practical application of it in the separation of certain materials from one another as a commercial process.

The Mordey mineral separator consists of a long row of electromagnets, each alternate magnet being excited by one phase of a two-phase current. Over this magnet is a long shaking tray, called a launder (see Fig. 13). If a powdered ore or mineral which comprises two ingredients, one having greater hysteresis than the other, is made to slide down this tray, the ingredient with greatest hysteresis is pushed outwards to the side of the tray and the other is not affected. Hence two streams of separated ingredients can be drawn off at the bottom (see Fig. 14).

The separator may be worked wet or dry. The launder is about 14 ft long and the magnets take from one to three horse-power to excite.

The following are typical results :—

A powdered ore, containing magnetic oxide of iron, specular hæmatite and micaceous schist, was treated and the hæmatite separated out, so that whilst the original ore

contained 40·4 per cent. iron and 0·1 per cent. of phosphorus, the concentrate contained 58·9 per cent. iron and only 0·01 per cent. of phosphorus.

Another ore, containing pyrites and pyrrholite, with 2·25 per cent. of copper, 2·54 per cent. of nickel, and 46·3 per cent. of iron, was separated into two products, A and B. An analysis of these showed: A = 94 per cent. copper, 52 per cent. nickel, 22·9 per cent. iron; B = 6 per cent. copper, 48 per cent. nickel, 87·1 per cent. iron.

The copper, therefore, is contained chiefly in one and the iron in the other. This could not be done by any ordinary form of magnetic separator.

In treating iron ores the magnetite and any specular hæmatite are readily separated from any

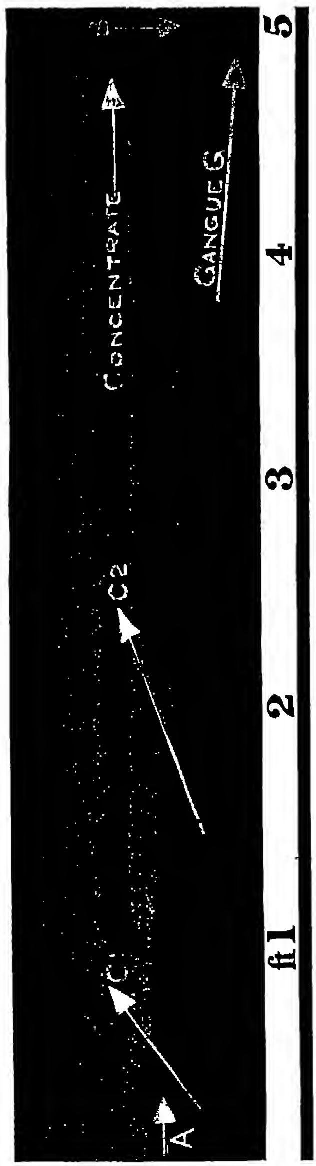


FIG 14.—View looking down on shaking table of Mordey separator.

A Indicates direction of feed and reciprocating motion
B Indicates inclination of table, about 1 in 20
C1 Path of highly hysteretic minerals
C2 " slightly "
G Non-hysteretic minerals

apatite present, thus effecting dephosphorisation by a simple operation.

It will be seen then that the scientific study of ferro-magnetic materials has yielded results which have been applied in extremely important practical inventions in electrical technology.

We seem to be able to do what we like with this common, yet unique, element iron, increasing or diminishing at will all the special magnetic qualities which distinguish it. At the same time we have made very little progress in the discovery of the particular mechanism which gives to iron its extraordinary magnetic qualities It is perfectly clear that magnetisation does not consist in the creation of a new property in the metal, but only in the arrangement in one direction of certain structures of atomic or molecular size. These structures are called Weber elements, or else magnetic carriers, but a better term would be *micromagnets*, because they are magnets of extreme minuteness. It seems as if this special quality in iron could be reduced by the admixture of some other metal such as manganese, and exalted by proper admixture of other metals, such as nickel, and even imitated as in the Heusler alloys by complex molecules of individually non-magnetic or feebly paramagnetic metals.

It has been proved that the form of the crystal lattice or arrangement of atoms of the metal to form micro-crystals has no definite relation to magnetic permeability. If the rotation of an electron in its orbit round the nucleus of an atom produces a magnetic field, then in most atoms these orbits are so arranged as to plane and direction of rotation that their effects neutralise each other.

On the other hand, in certain atoms or groups of atoms, there may be such an arrangement of electronic orbits as to bestow resultant magnetisation on the whole atom or molecule.

That is the most which can be said at present as to the ultimate cause of ferromagnetism.

Like the ultimate nature of an electric current it remains for the present almost, if not quite, an unsolved problem.

CHAPTER III

THERMIONICS

VERY few departments of scientific research work have yielded more remarkably interesting applications in electrical technology than that concerned with the emission of electricity from incandescent substances, the study of which has been called Thermionics.

It has been known for the greater part of a century that flame has conducting power for electricity. An old method for discharging or removing electric charge from insulators consisted in passing over them the non-luminous flame of a Bunsen gas burner or spirit lamp held in the hand A very important fact was, however, noticed by Professor Frederick Guthrie, in 1873. He discovered that if a red-hot iron ball was supported on an insulating stand, it could not retain a charge of positive electricity as long as one of negative electricity. That is to say, the positive charge leaked away more quickly than the negative charge At a bright white heat it could not retain, or lost equally quickly, both a positive and a negative charge Guthrie varied the experiment by charging a gold-leaf electroscope and holding near to it a platinum spiral, heated to incandescence by an electric current. He found that when the spiral was red hot it discharged negative electricity from the electroscope more quickly than positive, but that when the spiral was brilliantly white hot it discharged both positive and negative charges at an equal rate. From certain measurements made by him we can roughly estimate that at temperatures between 750° C. and 1,000° C an iron ball rapidly loses a charge of positive electricity, and at temperatures from 1,200° C. to 1,300° C. and

upwards, it loses both negative and positive charge very quickly.

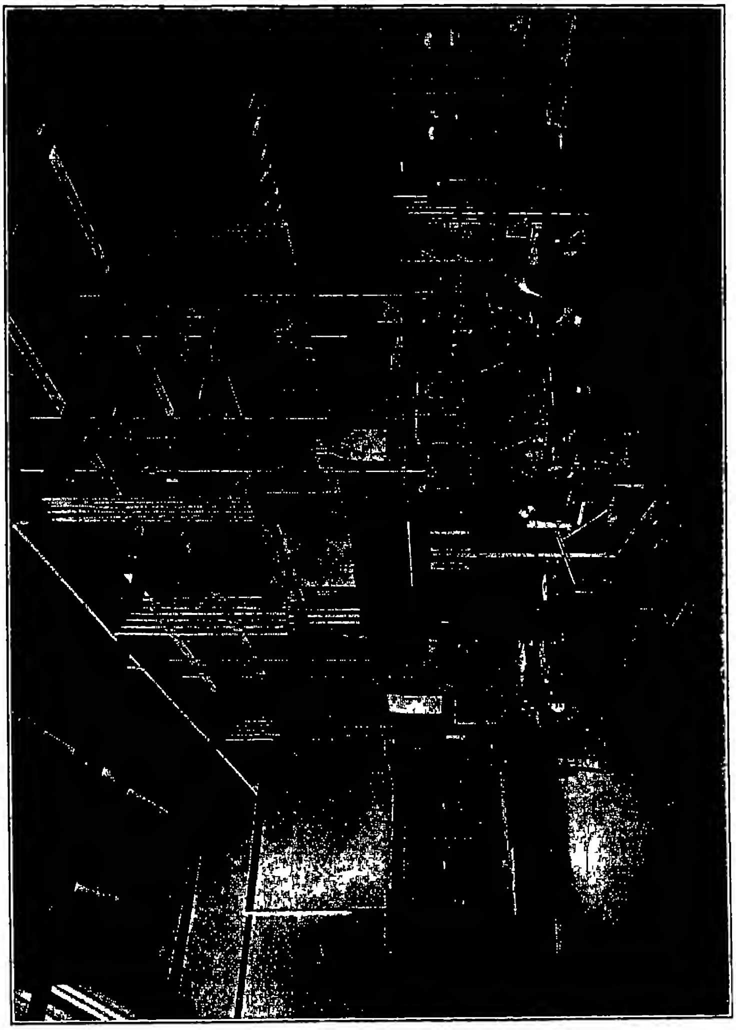
The experiment can easily be shown with a poker made red hot at the tip. If a gold-leaf electroscope is charged with negative electricity and the tip of the red-hot poker held near it, the negative charge on the electroscope induces a positive charge on the tip of the poker This induced charge escapes to the electroscope and neutralises the negative charge of the latter. If, however, the electroscope is charged positively, then the red-hot poker, held near it, will not discharge it so readily

This experiment can be converted into a lecture experiment by projecting on a screen the shadow of the leaves of a gold-leaf electroscope and then holding near the ball or plate of it a spiral of nichrome wire, which is made more or less incandescent at pleasure by a controlled electric current. Guthrie's observations were not capable of correct interpretation at the time they were made. About ten years later, Elster and Geitel, in Germany, carried out similar experiments inside a glass bulb, exhausted of its air, using a platinum wire heated by a current, which wire passed through the bulb, and had placed near to it a platinum plate carried on a wire sealed through the wall of the bulb. Elster and Geitel found that a metallic wire gave off *in vacuo*, positive electricity at or below a red heat and negative at higher temperatures.

They found that a carbon filament *in vacuo* gave off negative electricity at all temperatures.

Beyond recording a number of interesting facts, in which Guthrie's observations made in air at ordinary pressure were repeated in highly rarefied air, Elster and Geitel did not throw any light on the reasons for this curious difference in the thermionic emission of hot wires.

In the years between 1879 and 1883 the carbon filament incandescent lamp was invented and perfected in England by Swan and Stearn, aided by Gimingham, and in the United States by Edison and others. Swan



[*By courtesy of the General Electric Company, Ltd*

FIG. 14A.—A view of one of the valve exhausting rooms in the General Electric Company's Research Laboratory at Wembley, England.

and Stearn employed as a conductor a carbonised parchmentised cotton thread, viz., one that has been treated with sulphuric acid to destroy the fibrous structure of the thread. Edison used a thin fibre or slip of bamboo, first cut into a horseshoe or hairpin shape. These filaments were carbonised by being heated out of contact with air in a closed chamber, and then the carbon filament was mounted on copper terminal wires. joined to bits of platinum, and these sealed through the wall of a glass bulb, which was exhausted of its air. The filament was rendered incandescent by a current of about three-quarters of an ampere supplied at a terminal pressure of 100 volts to the lamps. It was very soon noticed that these carbon filament incandescent lamps blackened on the inside of the bulb very quickly when in use, and the more so if the terminal voltage was unduly raised. The "life" of the filament was found to be very short if run at a temperature much above 1,700° C. Moreover, if the terminal voltage was raised too much a bluish glow appeared in the bulb. In the endeavour to find out the reasons for this, Edison inserted a metal plate in the bulb, between the legs of the horseshoe-shaped carbon filament. This plate was carried on a platinum wire sealed through the bulb. He made the observation that if the filament was traversed and heated by a direct current, then if a galvanometer or current-measuring instrument was connected outside the bulb between the plate and the positive terminal of the filament a small current of a milliampere or two flowed through it. If the plate was connected through the galvanometer to the negative terminal of the filament, then no current, or at most a very small one, was found.

This observation has since been called the "Edison Effect," but Edison gave no explanation of it, nor did he make any application of it in practical Telegraphy or Telephony He simply recorded it in a United States' Patent application in 1883: U.S Patent, No. 307,031.

In 1882, the author of this book was appointed scientific

adviser of the Edison Electric Light Company, of London, formed to undertake electric lighting on the Edison system. This gave him the opportunity of exploring some of the physical effects connected with the incandescent electric lamp. One of the earliest facts noticed was that when a slight defect occurred in a bamboo carbon filament lamp on one side of the loop, so that extra resistance occurred there and a brighter incandescence at that spot, carbon particles were thrown off in straight lines from it.

These carbon particles were projected on to the inside of the glass bulb and blackened it. One side of the carbon loop, however, shielded the glass from bombardment from the hot spot on the other side of the loop, and the result was a white line devoid of deposit on one side of the bulb in line with the plane of the filament loop. The writer called this a "molecular shadow." Two Papers were communicated by him to the Physical Society of London on this matter, in 1883 and 1885. Meanwhile the author had begun a more careful examination of this so-called "Edison effect," and obtained a number of new facts about it. It was ascertained that the interposition of a mica screen between the negative leg of the carbon filament and the plate stopped almost entirely the effect, and it was shown that a grid or zigzag of platinum wire was effective, but not so effective as a plate.

The author also made the discovery that if the plate in the bulb was connected to one terminal of a large condenser charged positively, the other terminal of the condenser being put to earth, then when the carbon filament was rendered incandescent it instantly discharged this condenser even if it had a capacity of 10 microfarads charged to 100 volts.

These facts showed that negative electricity was being given off copiously from the incandescent filament, and other experiments showed that it was given off most from the negative side of the carbon filament and carried away in straight lines so that it could reach the collecting plate if the latter was at a distance of several centimetres, but

not if the plate was placed at the end of an elbow tube of glass leading out of the main bulb. Most of these experimental bulbs and lamps employed in this research by the author, between the years 1884 and 1890, are now placed in the National Science Museum, at South Kensington, London (see Fig 15) It was also shown that the same projection of negative electricity took place when a carbon filament was rendered incandescent in air at ordinary pressure, only in this case the filament was very soon oxidised and burnt up.

At a later date the author employed a Nernst glower, composed of magnesia and rare earthy metal oxides, in a similar experiment.

These experiments were shown and described with many others in a Friday Evening Discourse, at the Royal Institution of Great Britain, in February, 1890.

In the explanations of these effects given at that time the author assumed that the carbon atoms projected from the filament were the carriers of this negative charge, because at that date no other particles smaller than atoms were known.

It was not until 1899 that Sir J. J Thomson made public his great discovery of masses smaller than atoms, now called electrons, and that these were indivisible units of negative electricity. Sir J J. Thomson showed that incandescent carbon gave off *in vacuo* these electrons.

Hence it was clear that the emission from a carbon filament *in vacuo* at a high temperature is partly a throwing off of atoms of carbon and partly an emission of electrons The experiment of Edison and the author's discoveries with regard to it then received a sufficient explanation. The emission of electrons takes place most copiously from the negative leg of the carbon filament They carry negative electricity to the collecting plate and hence create a current flowing through a galvanometer connected in between the plate and the positive terminal of the filament. This is now called the thermionic emission from an incandescent substance.

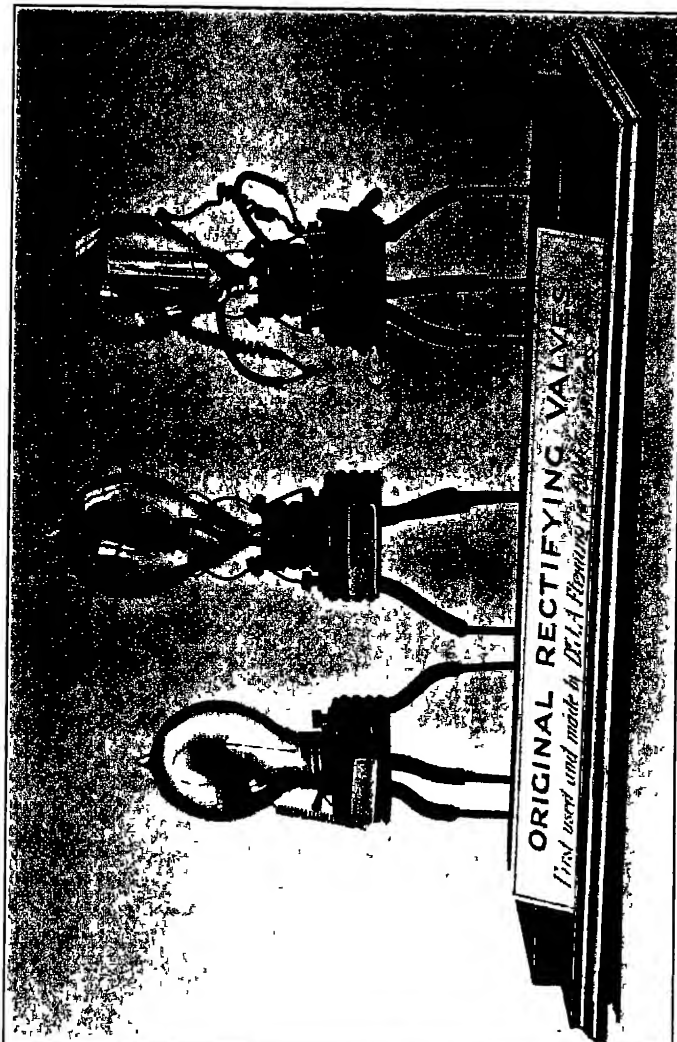


FIG 15 —Original rectifying thermionic valves first used by the author for rectifying high-frequency electric currents

Before proceeding to discuss the additional scientific work in connection with thermionic emission, it may be well to point out the manner in which it was first technically utilised by the author. It was clear that if there be

two electrodes sealed into an exhausted glass bulb, and if one of these is made incandescent, there will be a transference of electrons from the hot to the cold electrode. As far back as 1873, W. Hittorf, investigating the glow discharge in rarefied gases had found that in such a vacuum tube the resistance, when both electrodes are cold, may be many thousands or millions of ohms, and it will take an electromotive force of many hundreds of volts to send even a small current through the gas. If, however, one electrode is made incandescent and made the negative electrode, then an electromotive force of even a few volts will send a perceptible current through the gas.

The author confirmed this fact by constructing a tube of the following kind. At both ends of the tube a pair of small carbon filament loops were inserted, capable of being made incandescent by 12 volts or so. Each little filament was rendered incandescent by its own insulated battery. Then a third battery was employed which had its terminals connected to the middle points of the two pairs of carbon filaments at each end of the tube. A millimeter was inserted in that circuit to measure the third battery current.

If the carbon filament to which the negative terminal of the third battery was attached was made incandescent, an electric current of a milliampere or so flowed under an electromotive force of a few volts through the rarefied air in the bulb. If that negative electrode was left cold, then no measurable current flowed even with some hundreds of volts potential difference between the electrodes.

This experiment shows that the resistance of the rarefied gas resides chiefly at the negative electrode and that if the latter is made incandescent that resistance almost vanishes The author then made an instrument he first called an "oscillation valve," but later on a "thermionic valve," as follows: A small incandescent glow lamp was made with a loop carbon filament of such length and thickness as to be made brilliantly incandescent by 12 volts on the terminals (see Fig. 16). This loop filament

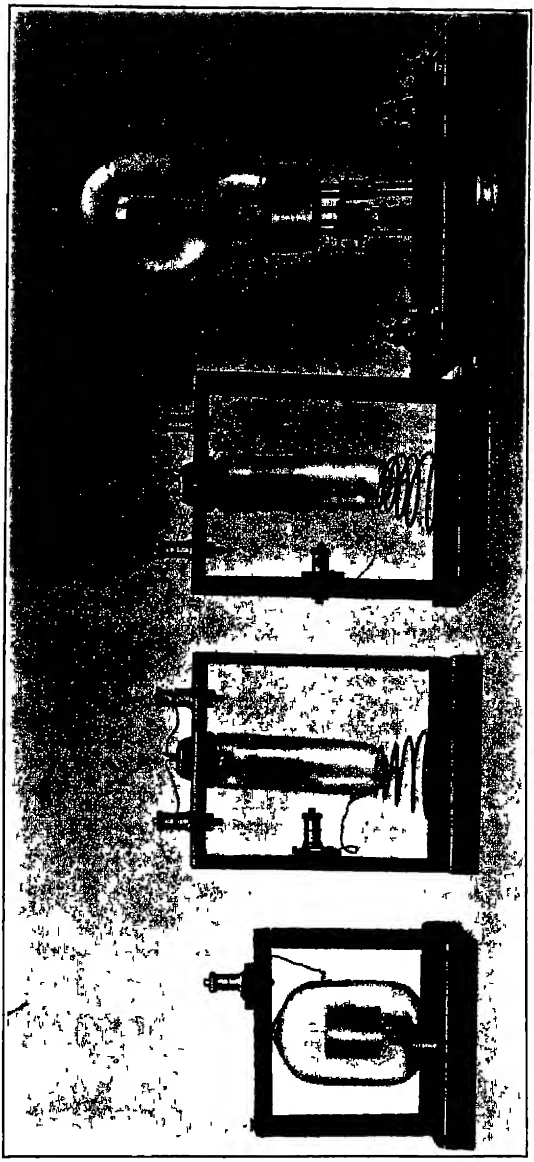


Fig 16 —Fleming rectifying thermionic valves made and used as detectors in wireless telegraphy in 1904.
N.B —The bulb on extreme right is a four-electrode valve invented later.

was surrounded by a metal cylinder close to, but not touching the filament, and this cylinder was carried on a third terminal, sealed through the bulb. When the filament was made incandescent, if a battery of a few cells, or even a single cell, had its negative pole connected to either terminal of the hot filament and its positive pole to the cylinder, then a current up to a few milliamperes flowed through that circuit. If the battery was reversed no sensible current flowed

It was generally found that if the cylinder was connected to the negative terminal of the filament (assuming this last to be incandescent by a direct current) then a very small current of a microampere or more flowed through this circuit, and it required a reversed E.M.F. of half or three-quarters of a volt to reduce this current to zero.

If the cylinder and filament were connected respectively to the terminals of a transformer or generator, giving a high frequency alternating current, then it was discovered that only one phase of the current could pass, viz , that half of the current during which the cylinder was connected to the terminal then positive of the transformer.

This operation the author called rectifying the current, because the current could only pass through the bulb in one direction. The arrangement was called a "valve" because that is a common term for a device which permits a flow of water, air, or steam to take place in a pipe in one direction only. It was at once found that this thermionic valve could rectify or convert into a unidirectional current alternating currents of any frequency, however high, and that it enabled such high frequency currents to affect a mirror galvanometer or a telephone

The author therefore applied it in 1904 as a means of detecting the electromagnetic waves used in wireless telegraphy.

When these waves, generated at a distant station with their magnetic component parallel to the earth's surface and electric component vertical to it, arrive at a receiving

station and fall upon the long vertical wire with lower end connected to the earth, called a Marconi aerial wire, they induce in the aerial very rapid oscillatory electric currents. To ascertain the existence of these feeble oscillatory currents we make use of some device called a detector. At that date (1904) two types of detector were in use, viz., the coherer and the magnetic detector. The former was rather capricious and difficult to manage, and the latter was not very sensitive, and could only be employed with a telephone to hear the dot and dash signals, but not with any recording instrument.

The author desired to invent some type of detector which would enable the signals by wireless telegraphy to be received with a mirror galvanometer or syphon recorder, as in the case of signals sent through submarine cables. To do this it was necessary to " rectify " the rapid oscillatory currents set up in the aerial, and before 1904 no means of doing this was known which was effective for currents of such frequency, viz., 100,000 to 1,000,000, as are used in wireless telegraphy.

It was at once seen, however, that this oscillation or thermionic valve provided the very thing required, and it was accordingly joined into a wireless receiving circuit as follows :—

Marconi had by that time discovered that in a receiving aerial it was best to cause the feeble aerial currents set up by the incident electric waves to induce other secondary currents in a syntonic or tuned secondary circuit, comprising a condenser of variable capacity, and the secondary coil of a transformer, the primary coil of which was inserted in the aerial. The author then connected the plate of his oscillation valve to one terminal of the said condenser and the filament to the other, inserting in this circuit a galvanometer or a telephone. The filament of the valve was rendered incandescent by a separate battery of a few cells.

At that time the system of wireless telegraphy generally in use was called the spark system, because the waves

were generated by the spark discharge of a condenser, repeated 50 to 500 times a second, each of which created a short train of electromagnetic waves sent out into space.

The oscillation valve at the receiving aerial then rectifies each of these trains into a short gush of electric current in one direction. These rapidly-repeated gushes of current create in the telephone associated with the valve a sound of the same pitch as the spark frequency. The Morse code alphabetic signals are then made by cutting up these trains of waves into long or short runs, corresponding to a dash or dot signal. The operator, therefore, hears in the telephone correspondingly long or short musical sounds, and is able to interpret these Morse signals into letters of the alphabet or words

If a mirror galvanometer is employed in place of a telephone, then it gives deflections due to the rectification of these trains of waves into unidirectional currents which, when intermitted to make Morse signals, give small or large deflections of the spot of light falling on the scale of the galvanometer corresponding to the dot or dash signal.

The readings are therefore taken as in the case of submarine cable working. In some cases the telephone is not inserted directly in the valve anode circuit but in the secondary circuit of a transformer, the primary coil of which is placed in the valve circuit between collecting plate and filament of the valve.

Such thermionic valve detectors were taken into practical use by Marconi's Wireless Telegraph Company very soon after their invention by the author. It had one great advantage over the coherer, viz., that it was not put out of adjustment by any strong "atmospheric" or stray wave, nor did it require any careful adjustment to be in a receptive state like the coherer or the magnetic detector.

Thus was born into the world an appliance of great practical use in wireless telegraphy, its beginning having been laid in a purely scientific study of blackened electric

glow lamps, and of the physical effects taking place in their working.

But this appliance itself proved to be of great physical interest to examine. In a Paper read to the Royal Society of London, in 1905 (see *Proc. Royal Soc. Lond.*, Vol. 74, p. 476, 1905), on the conversion of electric oscillations into continuous currents by means of a vacuum valve, the author gave the results of an examination of the relation between the electron current flowing through the vacuous space between the filament and the plate and the impressed E.M.F. in the circuit by means of curves, called the characteristic curves of the valve. These curves somewhat resemble in form the magnetisation curves of iron. They rise up rapidly at one point and then bend over, and the current finally reaches a *saturation* value beyond which it does not increase any more with the impressed E.M.F.

The reason is that at a fixed temperature of the filament there is a certain emission of electrodes from it. Under the action of an impressed E.M.F. these electrons are urged across from the filament to the plate, and the number so passing increases with the force. But a point is reached at which the number of electrons carried across per second is equal to the number coming out of the filament. After that point is reached, no increase in E.M.F. can take them across in greater number.

The only way to increase the electron is to increase the temperature of the filament.

There is therefore a close connection between the saturation current and the absolute temperature of the filament.

This was carefully investigated by Professor O. W. Richardson, who derived a semi-empirical formula from the consideration that the emission of electrons from a filament under heat was in some respects like the evaporation of water from a wet rope if the latter were placed in a hot locality.

One way of expressing this relation is as follows: If

N denotes the number of electrons emitted per second per square centimetre of surface of the filament when the latter is at an absolute temperature T, and the electron current is saturated, then the relation of N and T is expressed by—

$$N = AT^2\epsilon^{-b/T},$$

where ϵ is the base of the Napierian system of logarithms and A and b are specified constants for that particular material.

It was found that the result of experiments agree better with the formula—

$$N = A\sqrt{T}\epsilon^{-b/T}.$$

The constants A and b have the following values :—

Carbon . .	$A = 10^{34}$	$b = 7{\cdot}8 \times 10^4$
Tungsten .	$A = 1{\cdot}55 \times 10^{26}$	$b = 5{\cdot}25 \times 10^4$
Tantalum .	$A = 7{\cdot}45 \times 10^{25}$	$b = 5 \times 10^4$

Hence b is always not far from 50,000 but A is very variable. The quantity b is of the nature of a temperature. By very careful purification of a tungsten filament and heating it to the highest possible temperature Richardson found it was possible to increase the electron emission per second per square centimetre to the enormous value of 50×10^{18} or 50 million billion electrons.

The question then arises, What are these electrons ? Are they the free electrons which have been postulated to account for the electric conductivity of the metal ?

At one time it was supposed that they were due to impurities or to absorbed gases, but this has been proved to be not the case

From certain experiments by O. W. Richardson it is highly probable that these electrons are the conductivity electrons which escape, and that the process of sending an electric current through an incandescent wire is something like the process of passing steam through a canvas or porous pipe. There would be a continual leak through

the surface. We can regard the process from another point of view.

If there are free mobile electrons in the metal moving between the atoms or jumping from atom to atom, then there must also be ionised atoms—that is, atoms which have lost an electron from their planetary orbits and have therefore acquired a positive charge. Hence in a solid metallic conductor there must be three kinds of particles, viz., neutral atoms, ionised atoms, and perhaps free electrons. The electrons cannot easily escape from the metal because that would leave the metal positively charged. If, however, the temperature of the metal is raised and the electrons set more violently in motion then an electron near the surface it may acquire sufficient kinetic energy to make a dash for liberty and escape through the surface This will take place more easily if there is a cold metal plate near the surface, which is at a positive potential with regard to the incandescent metal. Also, if the source of that potential difference is a voltaic battery, capable of supplying negative electrons to the incandescent filament as fast as they escape from it. The continual exit of electrons from the surface is, however, hindered by the repulsion exerted by those which have escaped and fill the space around the incandescent surface. This is called a space charge.

If the positive potential of the cold plate or cylinder near or round the incandescent filament is raised, then the stream of electrons moving to it is increased, but cannot be increased beyond a certain limit, called the saturation current, unless the temperature of the filament is still further raised

Accordingly, the most suitable materials for producing this electron emission are those which will bear heating to the highest temperature

Carbon in the form of a carbon filament begins to evaporate very quickly when the temperature is raised above 1,700°, about the melting point of platinum, but tungsten can be heated without fusing or much

evaporation to nearly 3,000° C, provided it is in a very high vacuum. Hence, as soon as metallic tungsten was prepared in the form of wire it was discovered by the author to be particularly useful, as the incandescent substance of a thermionic emitter, since it could be heated by an electric current passed through it to any required temperature short of 3,000° C.

The form which the thermionic valve assumed about 1910, as given to it by the author, was a cylindrical glass tube, containing a hairpin-shaped loop of tungsten wire, this loop being surrounded by a cylinder of copper or nickel sheet, carried on a platinum wire terminal sealed through the glass wall of the tube (see Fig. 16).

This tube was exhausted to the highest possible vacuum for two reasons. First, because tungsten at a high temperature can combine chemically with both oxygen and nitrogen, and hence any residual air in the bulb will tend to shorten the life of the incandescent filament. In the second place, any residual air in the bulb is ionised by the electrons driven off from the filament; the positive residues of these ionised atoms are attracted violently to the filament and bombard it and assist mechanically to destroy it.

A very high vacuum valve is called a *hard* valve and a rather low vacuum valve a *soft* valve, the names being adopted from similar denominations in the case of Röntgen or X-ray bulbs.

It is possible to make hard valves quite identical, but not soft ones. The high vacuum necessary is now obtained by special forms of vacuum air pumps, but it is assisted by putting into the glass bulb a bit of metallic magnesium. This, at a final stage, is evaporated by heat and coats the interior of the valve with a silvery lustre.

Magnesium has the power of combining with both oxygen and nitrogen, and hence it absorbs and removes all the molecules of residual air which are left in the bulb after pumping. The effective construction of thermionic

valves is thus greatly facilitated by the discoveries of pure scientific chemistry.

Meanwhile, about 1907, a further technical improvement was made in the thermionic valve which converted it from a simple rectifier of electric oscillations or high frequency currents into a relay or amplifier. Lee de Forest, in the United States, had been following with very close attention the writer's work on the thermionic valve. In one of the experiments on the electron emission from incandescent filaments the author had employed a grid or zigzag of platinum wire in place of a plate in the Edison experiment. De Forest had the idea of including both a zigzag or grid of wire and also a plate into one bulb, which also contained a carbon or tungsten loop filament. The grid and plate were carried on separate wires sealed through the bulb. If a battery of cells has its positive terminal connected to the plate and its negative terminal to the filament, then a stream of electrons will flow out of the filament across the vacuous space and strike upon the plate. This constitutes the so-called anode current.

If the grid is made slightly negative in potential it will repel some of the electrons moving towards the plate and reduce the anode current. If the grid is made slightly positive it will increase the anode current. The potential of the grid, therefore, controls the anode current.

The relation between grid voltage and plate current can be represented by the co-ordinates of a curve, called the characteristic curve of the valve This type of grid valve is generally called a three-electrode valve or, by some, a triode for short to distinguish it from the two-electrode or Fleming or rectifying valve (see Fig. 17).

The characteristic curve of the three-electrode valve is shown in Fig. 18, in which horizontal distances, right and left, denote grid potentials or voltages positive or negative, and vertical distances denote anode or plate currents.

If we begin with the grid strongly negative, say 10 or 12 volts with respect to the filament, then the anode current is zero or very small If we gradually increase the

potential of the grid first to zero and then make it positive, the anode current increases but not indefinitely. Beyond a certain grid voltage, the plate current does not increase at all unless the temperature of the filament is raised. There is a certain range over which the characteristic curve is nearly a straight line, and for this range the variation of anode current is an exact copy of the

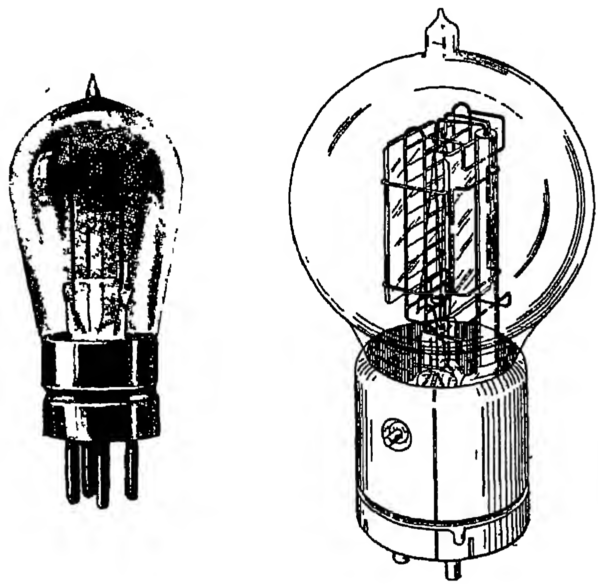


FIG 17 —Types of three-electrode thermionic valve containing a grid as well as filament and plate or anode.

mode of variation of the grid potential. The electrons are absolutely responsive to the changes in voltage of the grid. In a well-made valve a change in potential of the grid by 2 volts in the central part of the curve will change the plate current by at least 1 milliampere (see Fig. 18). The steepness of the straight part of the characteristic curve is therefore very important, because it implies a relatively large change in anode or plate current for a small change in grid volts. The slope of the characteristic

curve is denoted by the letter a and is sometimes called the amplification factor of the valve.

Then again, if the grid voltage is kept constant the plate current will increase with the plate potential or voltage, and this is determined by the effective internal resistance of the valve between filament and plate. There are then three important quantities which have to be determined,

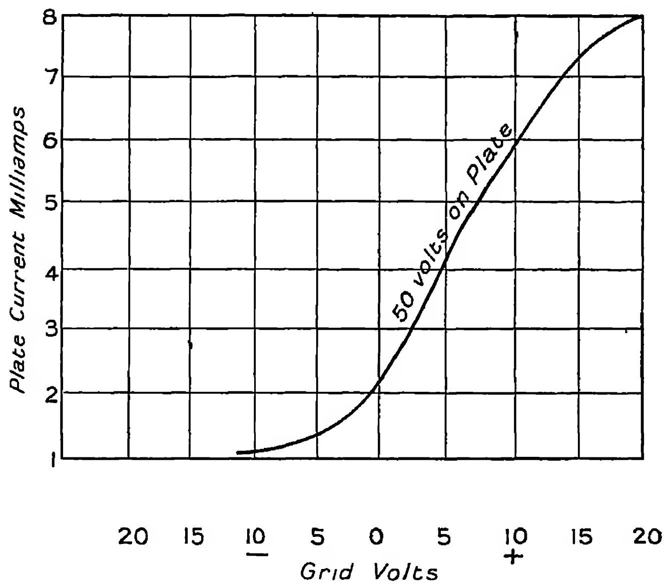


FIG 18 —The characteristic curve of a three-electrode thermionic valve.

and these are the plate current, plate potential and grid potential and two subsidiary quantities, viz , the characteristic slope and the valve internal resistance. The latter is not a constant quantity like metallic resistance, but is dependent on the plate potential or plate current.

The necessity for employing a high plate potential, 40 to 100 volts or more, is a great drawback to the use of the three-electrode valve.

We require then two separate batteries, one of about

4 to 6 volts, which is generally two or three storage cells. The current from this battery heats the filament to incandescence. Then we require another battery, comprising generally thirty to seventy or more dry Leclanché or secondary storage cells to provide the plate voltage of 60 to 100 volts or more. The storage cells require continually re-charging and it is not easy to have this done in out-of-the-way localities. Then the dry cells lose their electromotive force either by internal short circuits or the wearing away of the active materials, viz., zinc, and carbon covered with peroxide of manganese.

Scientific research has therefore been directed to overcome these difficulties and objections.

In the first place, valves have been invented with filaments called *dull-emitters*, which only require a very small current, from 0·12 to 0·25 ampere, to bring them to suitable dull redness or low incandescence. It was found that if metallic thorium is incorporated with the tungsten in making the filament it enormously increases the electron emission at the same temperature compared with a pure tungsten filament. In the manufacture of these thoriated filaments nitrate of thorium is mixed with oxide of tungsten in certain proportions and then heated in a current of hydrogen gas to reduce them to the metallic state. The fine metallic powder thus obtained is then heated and hammered to a solid condition and finally drawn into wire through diamond dies.

After being prepared the wire is heated to a temperature of 2,600° C. for a short time, and then lowered to 2,000° C., the thorium, which is then present to the extent of about 1 per cent., seems to work its way to the surface and forms a layer which facilitates the escape of electrons in some way from the heated metal so that the emission per square centimetre of the thoriated filament at a dull red heat is as great as that from pure tungsten at a brilliant white heat. Hence the name "dull emitter" valves. These valves are now made to operate with a filament current of not more than about 0·12 ampere,

and the filament can be heated to the required tempera-ture by a couple of Leclanché cells, such as are used for working electric bells.

Another type of filament has been much used in the United States and elsewhere which is the outcome of much scientific research.

It was discovered by Wehnelt, in Germany, that when a platinum plate has a speck of lime put on it and is used as a cathode in an exhausted tube the thermionic emission is very large from the lime-covered part of the metal when it is heated *in vacuo*. The same is true of the oxides of barium and strontium which are chemically similar to lime, which latter is the oxide of calcium.

Accordingly, the Western Electric Company in the United States of America, developed a method of valve filament manufacture out of this observation as follows:—

A platinum-iridium wire is rolled out into a thin strip and coated with a mixture of nitrates of barium and strontium. It is then heated to reduce to the condition of oxide and the coated strip mounted as the filament of a valve with grid and plate on a highly exhausted glass bulb. Such oxide-coated filaments can be worked at a dull red heat, and the oxide, in some way not yet quite understood, facilitates the escape of electrons from the metal (see Fig. 19).

It may be observed that both thorium and barium stand in close relation, chemically, to radium, the chief radio-active element.

It has been a strongly-nourished hope that we might some day find a material which would copiously emit electrons from its surface *in vacuo* without being heated at all, and so give us what is termed a "cold valve." Probably this could be done if radium was cheap enough to use commercially instead of being very sparse and extremely costly.

The thermionic three-electrode valve is employed in four ways in radiotelegraphy and telephony, viz., (i.) as a radio-amplifier or magnifier of high frequency oscillations,

(ii) as a detector of electric oscillations ; (iii.) as a low frequency amplifier ; and (iv) as a generator of electric oscillations. If we connect one coil of a transformer, comprising two overlaid coils of wire wound on a bobbin, with the filament and the grid of a three-electrode valve

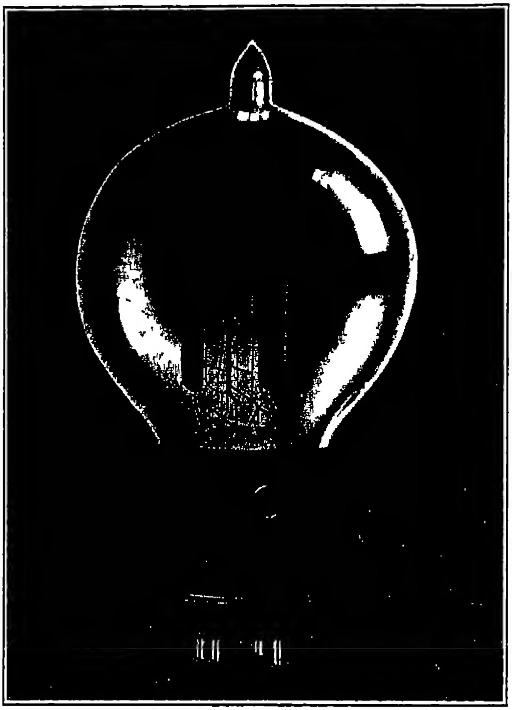


Fig. 19 —A three-electrode thermionic valve with an oxide coated or Wehnelt filament

and one coil of another transformer to the filament and plate, inserting in the latter circuit a high tension battery with negative terminal on the filament side and positive terminal on the plate side, then a small high-frequency sent through the primary coil of the first transformer will create a small alternating voltage which is applied to the grid. This then will cause similar fluctuations in the

direct current flowing in the plate circuit, and these will generate in the secondary circuit of the transformer connected thereto another alternating current. It is possible to so arrange matters that the secondary current in the second transformer is an exact copy in its mode of variation, but on a magnified scale, of the current entering the primary coil of the first transformer.

This magnification or amplification of current takes place in consequence of the fact that the battery in the plate circuit can supply power. The three-electrode valve acts like the instrument called in telegraphy a relay. But the valve can act as a relay for high-frequency currents, whereas the ordinary relay, which depends on electromagnets, cannot so act.

Accordingly we can amplify not only high-frequency but also low-frequency currents by it, and telephonic or speech currents as well. Hence the three-electrode valve has become of enormous use in ordinary telephony by wires as a telephonic repeater or relay The three-electrode valve can also act as a rectifier or detector of high-frequency oscillations in the following way:—

Suppose we give to the grid a small negative potential or *bias*, which brings the working point down to the lower curved part of the characteristic curve.

If then we superimpose on this permanent bias an alternating potential or voltage it will be clear that a permanent negative bias means that the anode current is so small that it cannot be decreased but can be increased by making the grid less negative

Accordingly, an alternating voltage put on between grid and filament causes the anode current to increase by little pulsations, or increases its mean value. Suppose then we have a receiving telephone in the plate circuit and that the potential applied to the grid is of the nature of a rapid high-frequency oscillatory potential the amplitude of which varies in accordance with the wave form of any speech or musical sound of acoustic or low fre-

quency, we should then hear in the telephone these speech or musical sounds.

In the third place we can employ a third valve to amplify these rectified or speech or musical vibrations.

Accordingly, a broadcasting receiving set contains usually at least three thermionic valves. The first valve amplifies the high-frequency oscillations due to the so-called carrier waves. This is called the radio-amplifying valve. The second valve, called the detector, rectifies the high-frequency oscillations, and the third valve, called the note amplifier, amplifies the low-frequency speech or music currents, which can affect the receiving telephone in the plate circuit of the last valve. The power necessary to effect these amplifications comes from the high tension battery in the plate circuits of the valves

We have yet to explain how scientific research into the wonderful properties of this thermionic valve has revealed an additional power in it of creating electrical oscillations.

We have shown above that if a very feeble alternating current is passed through one coil of wire of a transformer, the associated secondary coil of which has its terminals connected, respectively, to the grid and filament of a valve, and if there is a similar two-coil transformer, one circuit of which is in the plate-filament circuit, which must include a battery, then the feeble current in the primary coil of the grid transformer will create a similarly varying but stronger current in the secondary coil of the plate transformer.

If, then, we connect back in the right direction the secondary terminals of this plate circuit transformer with the grid and filament, we have a self-acting arrangement in which variations of current in the valve plate or anode circuit create variations in grid potential, which latter, in turn, maintain and exalt the plate current variations The reaction is very similar to that which takes place in the case of the cylinder and piston and slide valve of a steam engine. The motion of the slide valve to and fro admits the steam first at one end of the cylinder

and then at the other, thus moving the piston backwards and forwards. But this motion of the piston is transferred to the slide valve, so that the engine becomes self-acting and maintains itself in motion so long as the steam pressure is kept up.

The thermionic valve becomes therefore an appliance by which we can generate electric oscillations of high frequency and of any required energy from the power supplied by a direct current battery or a low-frequency electric current rectified by a Fleming valve.

It has been found that when a coil inserted in the plate circuit of a three-electrode valve is brought near to a coil inserted in the grid circuit, the direction of mutual induction of these two circuits being such as to tend to produce self-maintained oscillations, if the coils are not quite close enough to start these oscillations the valve then becomes more sensitive as a radio-amplifier or detector.

This is called retro-active or regenerative coupling of the two circuits or of the valve.

In any receiving set in which, however, this coupling exists, care must be taken not to pass the limit at which the valve begins to self-oscillate, by bringing the two coils which are respectively in the grid and plate circuits too near together. If this is the case then violent oscillations are set up in the receiving aerial to which the set is connected and electric waves radiated, which create noises in the telephones of other neighbouring receiving sets

The construction of very large thermionic valves for the production of electric oscillations, or power valves, as they are called, has been greatly assisted by certain scientific researches, which have had a most important bearing on their manufacture (see Fig. 20). In a highly exhausted or "hard" valve when used with a high voltage battery in the anode circuit there is a powerful stream of electrons emitted from the filament which strike against the anode cylinder. The energy so expended soon makes the anode cylinder red hot, and if continued for any length of time may melt it.

Since the cylinder is enclosed in a high vacuum it can only get rid of its heat by radiation.

It was accordingly seen that a great advantage would ensue if the anode cylinder could form part of the exhausted bulb, and then it could be kept cool by cold water or air or oil applied to the outside The scientific problem

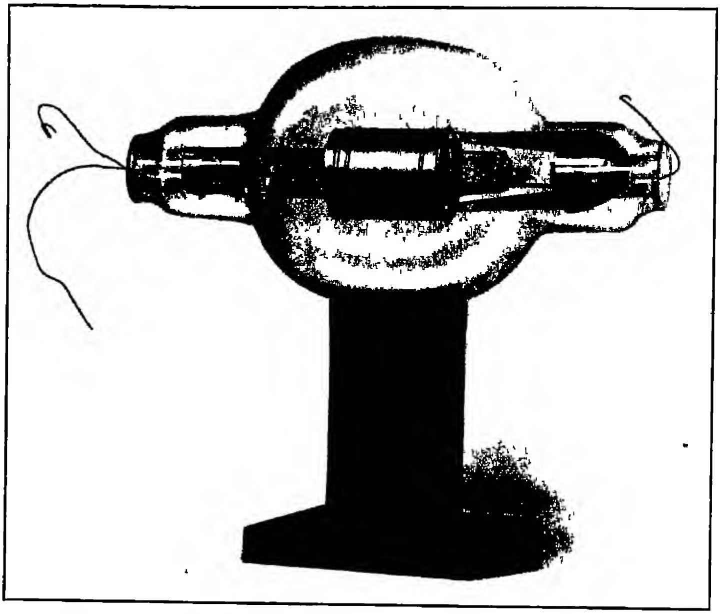


FIG 20.—Large glass bulb three-electrode generating thermionic valve, as made by the Marconi-Osram Valve Company, Ltd.

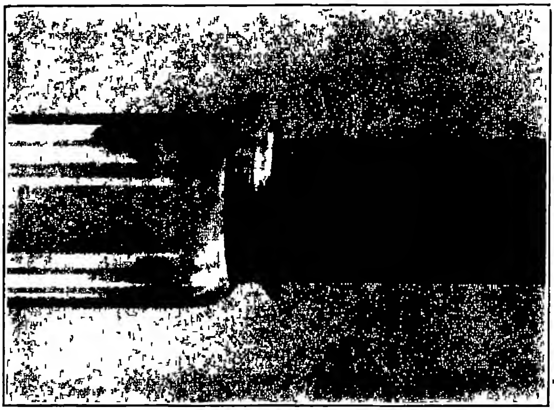
was then to find a method of sealing metal to glass. To effect this, two conditions must be satisfied First, the metal when hot must be "wetted" by molten glass, and secondly, the metal must have the same coefficient of expansion with heat as glass, or else the two will separate as the joint cools after heating. Up to a few years ago the only metal which could be sealed to glass or sealed through glass in the form of a wire was platinum. But

platinum has now become too rare and expensive to be used for industrial purposes. Amongst other metals it was found that copper, when clean, is "wetted" by molten glass, that is, it sticks to it. Nevertheless, copper has a different coefficient of expansion from lead glass, and only fine copper wires or very thin sheets of copper can be sealed to glass. Many years ago, about 1895, however, a French physicist, M. C. E. Guillaume, studied the thermal expansion of the nickel-iron alloys

He found that a certain nickel-iron alloy having the composition: nickel, 36 per cent.; iron, 63 per cent.; with 0·5 per cent. of carbon, and 0·5 per cent of manganese, has a coefficient of thermal expansion which is extremely small, only 87×10^{-8}. This alloy is now called *Invar*, and is used for making measuring rods, surveying tapes and clock pendulums, and other such-like things the length of which must not alter with temperature. Guillaume also discovered that for the proportions, nickel about 45 per cent., iron about 55 per cent., the coefficient of thermal expansion was the same or very nearly the same as that of lead glass.

Combining together these two scientific facts it has been found possible to make a metal cylinder which can be sealed to glass as follows: A nickel-iron or invar tube is closed up at one end so as to form a large thimble. The unclosed end has its edges sharpened, and is electrically coated with copper. This tube can then have its open end sealed to a lead glass tube of the same diameter, and through the closed end of the latter, invar copper-coated wires can be sealed in to support the filament, and the grid, in the form of a cylinder of metal gauze, placed round it (see Fig 22). The external metal anode cylinder can be jacketed so that it can be cooled by circulating water or oil. These metal bulb valves are now made in very large sizes so as to supply when worked in parallel many hundreds of horse-power in the form of high-frequency currents to aerial wires to radiate powerful electric waves for wireless broadcasting, and long distance

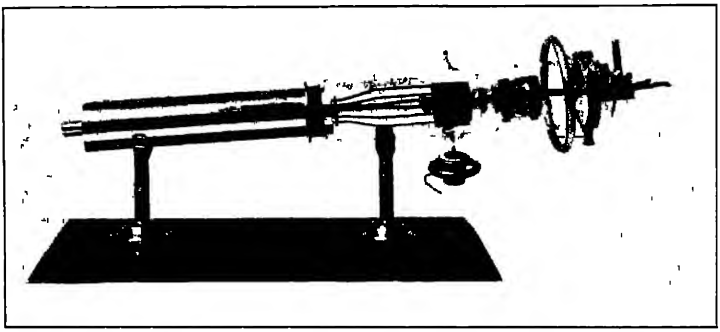
wireless telegraphy on the all-round or beam system, with long or short waves. Thus the combination of results



[By courtesy of the General Electric Company, Ltd

FIG 21—A joint made between a lead-glass tube (left) and a coppered invar tube (right)

of purely scientific investigations has finally led to the construction of a very wonderful piece of apparatus in the



[By courtesy of the General Electric Company, Ltd

FIG 22—An external metal anode valve, the anode sealed to a glass continuation forms part of the bulb The anode can be kept cool by a water jacket

form of the high power water-cooled thermionic valve for generating electric oscillations (See Figs 22 and 23.)

The three-electrode valve has been the subject of the

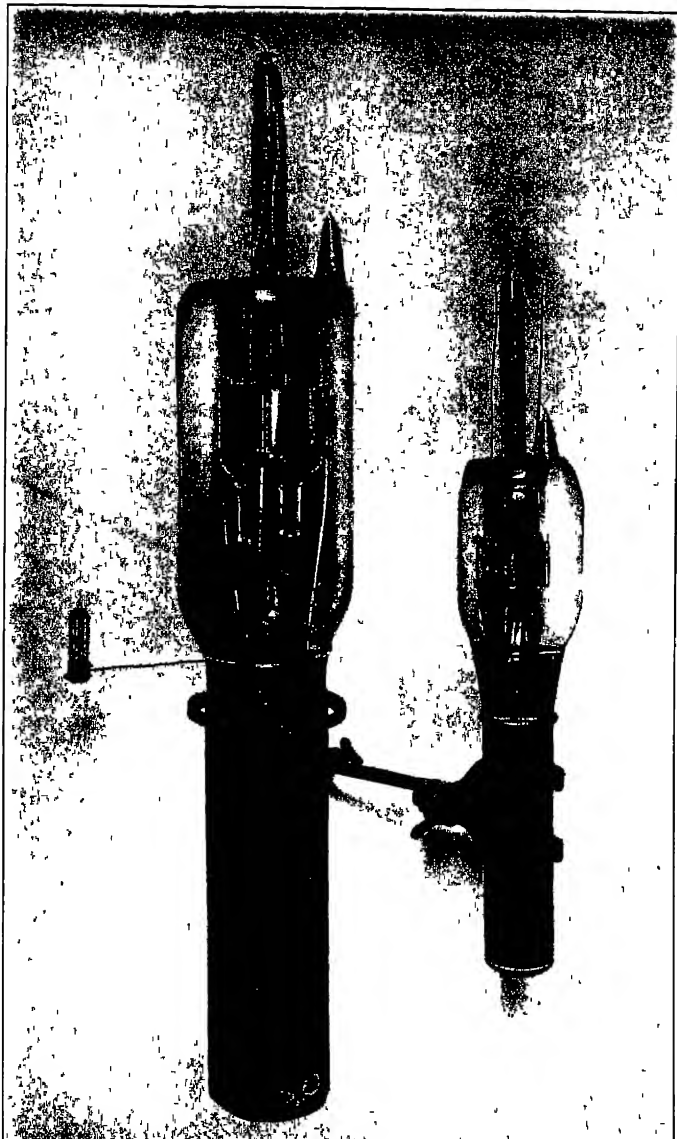


FIG. 23.—Metal-glass bulb three-electrode thermionic valves with external anode which can be cooled by water or oil passing through an enclosing jacket. (The jacket has been removed to expose the anode.)

most careful scientific investigations with the object of determining the principles upon which it acts. The peculiarly valuable property is that the amplifying power can be almost indefinitely increased by coupling valves in series with either two-coil transformers or high resistances and condensers. The simplest method is to insert one coil of a two-coil transformer in the plate circuit of a valve and then connect the grid and filament of the next valve to the secondary coil of that transformer and repeat the mode of connection for three, four or more valves. Hence the variations in plate current of the first valve are made to create variations in grid potential of the second valve, and these again create similar variations in the still stronger anode current of the latter valve.

If the amplifying power of each valve, which is determined by the steepness of the slope of the characteristic curve, is represented, say, by the number 5, then the amplifying power of the two coupled valves is five times five, or twenty-five, and of three valves in series is 125 In this manner a series of five or seven valves provides an enormous magnifying power for feeble currents or potentials.

It is this which enables us to use a so-called frame aerial, consisting merely of a few turns of insulated wire wound on a square frame to pick up broadcast electric waves from stations at a great distance. We can use, say, four valves in coupled series as radio amplifier, then a single detecting valve, and then two valves in series as note or low-frequency amplifiers. A still greater sensitivity is obtained by the use of re-active coupling, in which the final plate circuit is caused to re-act on the first-grid circuit by the indentive action of two coils.

In this case, however, we always run the risk of making the coupling too close, and then the valves will begin to set up self-produced oscillations or " howl," as it is called. The object of the super-regenerative arrangements of Bolitho, Armstrong and others, is to enable this coupling to be made close without setting up these self-produced

oscillations. When the valve is just on the point of oscillating it is more sensitive as an amplifier and detector. In one of the Armstrong super-regenerative circuits there is a valve with plate circuit coupled back to the grid and tuned for the wave length of the high-frequency used, say, 1,000 metres or less. Coupled inductively to the plate circuit of this active valve there is a second oscillating valve tuned for a frequency low compared with radio- or wave-frequency but high compared with the audio- or speech-frequency, say, 15,000 per second. This valve, called the control valve, puts an E M.F. either with or against the effective E.M.F. in the plate circuit of the first or active valve, so that the self-oscillations are alternately permitted or helped and checked

The self-oscillations therefore never increase to the point at which they cause mischievous radiation from the receiving aerial.

The actual detection and rectification of the changes in amplitude of the carrier wave, which constitute the speech waves, is achieved by a third valve having its grid connected to a third or tertiary coil on the transformer inserted in the receiving aerial circuit.

For further details of this super-regenerative circuit special books on valve circuits must be consulted. A rather different method of achieving the same object has been devised by M. Flewelling, which is claimed to employ fewer valves

In the Armstrong scheme the arrest of the incipient electric oscillations is brought about by the introduction of an electromotive force into the plate circuit, but in the Flewelling scheme it is done by giving the grid a sufficient positive voltage to force up the working point high on the curved part of the characteristic curve The self-oscillations of a valve can only be set up if the grid voltage is such that the plate current can be equally well increased or diminished by changing the potential of the grid. On looking at the diagram in Fig 24, it will be seen that the plate battery can communicate its potential to the

grid through a combination of condensers C_1, C_2, C_3, C_4, and resistances R_1, and R_2. Hence the grid tends to become positive in potential. But then it attracts electrons and again becomes neutralised, and the self-oscillations start up again, but no sooner have they started then they are checked again. The valve is then kept in a condition in which it continually starts

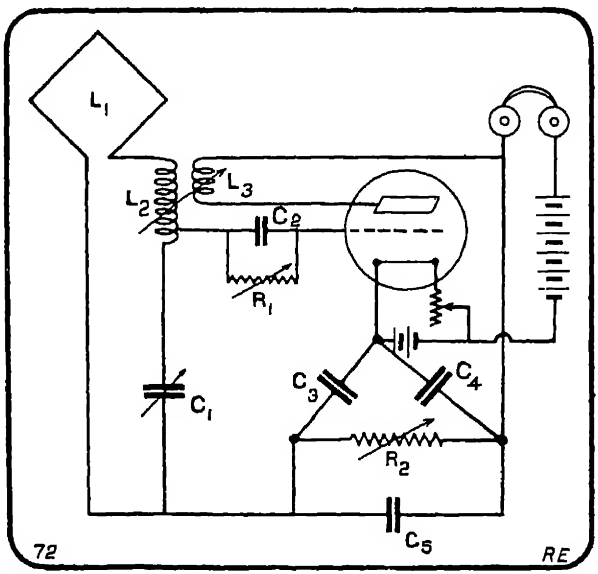


FIG. 24 —Super-regenerative circuit of M. Flewelling employing only a single valve

oscillating and is then stopped. At the same time it also acts as a rectifier or detector, and one single valve acts as oscillator, controller and detector, and forms a very sensitive receiving arrangement.

Very closely connected with these schemes for regenerative coupling is the method of valve working, called the *neutrodyne* method. In considering the operations of the three-electrode valve it will be seen that the inductive coupling of the plate and grid circuits by coils having

mutual inductance is not the only way in which self-oscillations can be set up.

There is an electrostatic coupling due to the fact that when the plate is at one potential, say, positive, it tends to make the grid negative by electrostatic induction. Hence, self-oscillations may by this means be produced.

If we consider a receiving valve circuit such as that shown in Fig. 25, we see that the scheme of circuits can be re-drawn as in Fig. 26 If then we supply to the valve circuit scheme in Fig. 25 an extra condenser C_3, represented by two parallel lines in the diagrams, we may notice that it completes the symmetry of the arrangement, so that oscillations set up in the circuit LC_2 by the incident electric waves cannot set up any oscillations in the plate circuit comprising the condenser C_1 and the inductances L_1, L_2, provided that the ratio of the sections L_1 L_2 of the inductance are in the same ratio as the capacity of C_3 is to the capacity C_4 between the plate and grid of the valve.

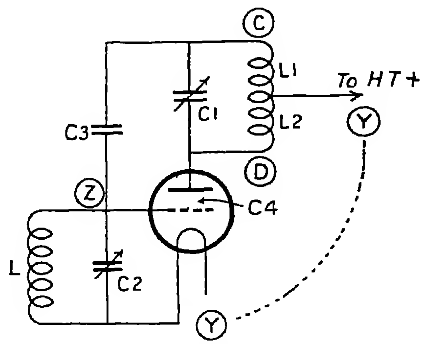


FIG 25.—A thermionic valve receiving circuit in which there is capacity between the grid (dotted line) and plate or anode (black line) denoted by C_4 and this is neutralised by an extra condenser C_3

The condenser C_3 tends to neutralise the capacity between the plate and grid. Hence the term *neutrodyne* applied to this mode of connection. It is impossible to mention within the short limits to which this chapter must be confined a tithe of the scientific researches connected with the thermionic valve or the practical inventions which have resulted from them.

One of the most important of these improvements is the double-grid or four-electrode valve, in which there are two

independent grids interposed between the filament and the plate. This mode of construction can give us valves of extraordinary amplifying power so that by means of two or three of them we can obtain immense powers of reception of feeble radio waves without the risks or complications connected with re-active coupling as devised by Captain H. J Round

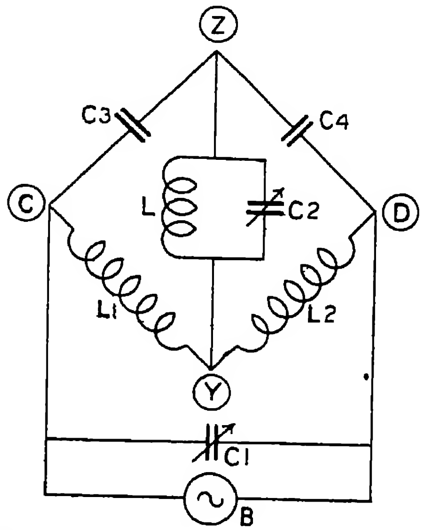


FIG 26.—A bridge circuit in which an alternator B produces no current in the bridge LC_2 provided the two capacities C_3, C_4 have the same ratio as the inductances L_1, L_2 The letters in Figs. 24 and 25 denote corresponding points or branches.

Also the same type of valve in the hands of Messrs. Dowding and Rogers has been able to produce a receiving scheme, called the "Unidyne" receiver, in which no high voltage battery is required in the plate circuit at all. In the method of working called the "Dual" system of amplification, one single valve is made to perform the two functions of amplifying the high frequency or radio-oscillations, and also the low frequency or audio-oscillations when using a simple galena crystal as a detector

The whole effort of those whose attention is directed to the design of receiving circuits is, therefore, to simplify the arrangements as much as possible.

The thermionic valve therefore, in its forms of two-, three-, or four-electrode, is the outcome of purely scientific investigations on the escape of electricity from hot bodies. The application of those researches has been to give us one

of the most remarkable electrical appliances yet invented. It possesses the most extraordinary powers of detecting almost immeasurably small high-frequency electric currents or potentials, and has enabled us to construct appliances which enable music and the human voice to be transmitted half round the world without interconnecting wires.

It has made of the whole world one vast auditorium in which a single voice can make itself heard. But it has done more: it has provided us with a fresh scientific instrument of not less value than the telephone or galvanometer for detecting the presence of electric currents undetectable by any other means and, therefore, enormously added to our instrumental appliances for pure scientific research.

CHAPTER IV

THE GLOW AND ARC DISCHARGE

THE scientific study of the electric discharge through gases and vapours in the forms called the glow and arc discharge has led to many technical applications of great importance, and the relation of some of this scientific research to electrical engineering we shall briefly pass in review in this chapter

If two metal surfaces, say, two metal balls, are placed at a short distance apart in some gas or vapour, and if a gradually increasing difference of potential is created between them, then at a certain voltage the insulating power of the dielectric gives way and an electric discharge or current passes which may take one of three forms, viz., spark, glow or arc, according to the conditions of the experiment.

If the gas is at atmospheric pressure and the source of electricity can only supply slowly or a very small current, that is, if the generator has a very high internal resistance, then the discharge takes the form of a spark, which is repeated again as the voltage or potential difference of the ball rises. The chief technical application of this spark at present is to fire the mixture of petrol vapour and air in internal combustion engines.

It is provided by so-called magnetos, which are small dynamos with permanent steel magnets and armature coils of very fine wire of great length, giving an E.M.F. of several thousand volts.

If the generator, whether direct or alternating current, is employed to charge a condenser or Leyden jar, and if the condenser is discharged through a low resistance circuit having a small air gap in it, then a discharge

spark is produced which is oscillatory, that is to say, the discharge is not a single unidirectional motion of electricity, but a to and fro motion, which gradually dies away, as first predicted by Lord Kelvin in 1851. The sparks may succeed each other rapidly, and each spark creates a train of electric oscillations.

The number of sparks per second is called the spark frequency, and the number of oscillations per second or reciprocal of the time duration of each complete oscillation is called the oscillation frequency.

The latter frequency (n) can be calculated when we know the capacity (C) of the condenser which is discharging, and the inductance (L) of the circuit through which it discharges for n is equal to $\frac{1}{2\pi\sqrt{CL}}$ This oscillatory spark has its practical application in so-called spark wireless telegraphy. For, if the oscillations set up by a condenser of suitable capacity discharge through one coil of a two-coil transformer, the secondary coil of which has its terminals connected respectively to an aerial wire and to an earth-plate, then when the inductances of the two circuits are properly adjusted so that they are in syntony, the oscillatory discharges of the condenser will create oscillations in the aerial wire of like frequency, and these will radiate their energy as electric waves.

It will not be necessary to explain the details of this spark telegraphy at greater length, because there are a very large number of books which deal with it copiously to which the reader can refer.

The original suggestion that electromagnetic waves could exist, comprising periodic variations of electric force and magnetic force at right angles to each other and to the direction of propagation of the wave, was made by James Clerk Maxwell in 1865, but it was not until ten years or more later that G. Fitzgerald made the suggestion that Maxwell's electromagnetic waves might perhaps be created practically by the oscillatory discharge of a condenser. We had then to wait a further ten years, until

1886 or 1887, before H. Hertz discovered the form of con denser and circuit which would create this radiation.

If two flat metal plates are placed with planes parallel and very near to each other in air this constitutes an air condenser. If the two plates are connected by a short low resistance wire, and if the condenser is charged with electricity and then discharged through this wire, high-frequency electric oscillations are created in the wire, but the energy stored up in the condenser is dissipated as heat in the wire and very little of it is thrown off from the circuit as electromagnetic waves. Such a closed circuit is said to be a bad radiator. It is comparable with a highly polished silver vessel containing a hot liquid which cools slowly because it radiates very little

If the metal plates instead of being placed close to each other are kept as far apart as possible, with their surfaces in the same plane, but are joined as before by a low resistance wire, then when electric oscillations are set up in this system it gets rid of nearly all its stored energy in the production of electromagnetic waves. It is said to radiate well. It is comparable with a vessel coated on the outside with lampblack and containing some hot liquid. This would cool very quickly because a black surface is a good radiator. The arrangement is called a Hertz oscillator or radiator, and as soon as he had made known its powers of creating Maxwell's electromagnetic waves physicists all over the world began to experiment with it and to devise means for detecting and rendering evident the electric radiation it could produce.

Some ten years later Marconi made the first technical application by means of a modified form of Hertz radiator called a Marconi aerial. He buried in the ground a metal plate, and he affixed to a mast by insulators a metal cylinder. These two metal surfaces constituted the plates, widely separated, of a condenser. He connected them by a wire in which was a spark gap formed of two balls. When he charged this condenser by means of an induction coil, the condenser discharged across the spark

gap and the resulting electric oscillations created electric waves which radiated in all directions. He modified and greatly increased the sensibility of the metallic filings coherer invented by David Hughes and re-invented by E. Branly and Sir Oliver Lodge. He made use of this as a detector and invented a simple method of sending out waves in short or long groups or trains, and causing these to increase the conductivity of the coherer at a distant station, and by its aid to control a telegraphic relay and Morse printing telegraph receiver, so as to record alphabetic signals in Morse code.

Thus was born into the world the first elementary form of electric wave wireless telegraphy, which has since been developed into a marvellous means of intercommunication between far distant places on the earth's surface.

At a little later date, Marconi combined together the energy storing powers of a closed condenser circuit, with the radiating properties of an open circuit.

He connected the terminals of a battery of Leyden jars or some large capacity air or oil condenser with the terminals of one coil of wire of a single turn wound on a wooden frame, and connected the ends of another overwound coil of ten or twenty turns or more with an aerial wire and with an earth plate. These two circuits were carefully tuned so as to have the same natural period of electric oscillation.

When oscillations were set up in the closed condenser circuit by charging and discharging the condenser across a spark gap inserted in its circuit, then the prolonged trains of oscillations induced others of like kind in the open or aerial circuit, and this radiated trains of electric waves, each comprising a great many oscillations or so-called feebly damped trains of waves. Special revolving spark gaps had subsequently to be invented to quench out the electric arc, which tended to leap across the spark gap, for as long as this endured it was impossible to charge the condenser again.

This form of powerful spark oscillator served, however,

to bring into existence long distance wireless telegraphy until it was replaced by the continuous wave valve generator already mentioned in the previous chapter.

The second type of electric discharge is called the glow discharge and takes place when a source of electromotive force, which has a rather high internal resistance and can, therefore, only supply a small current, is connected to two metallic wires sealed into the ends of a glass tube containing rarefied gas of some kind.

These wires are called the electrodes, and the arrangement is usually called a vacuum tube, although the word vacuum is relative. The phenomena exhibited in the tube when the electromotive force is unidirectional, that is, always in the same direction, depend upon the pressure of the residual gas. If we begin with the gas at a pressure of about a millimetre or so and gradually reduce the pressure, the following are the effects observed :—

The tube becomes full of a glow of light, the colour of which depends on the gas used.

This glow extends from the positive terminal or anode right along the tube. Near the negative electrode or cathode there is a dark space, called the Faraday dark space, and the negative electrode itself is covered with a closely adhering glow, called the cathode light.

If the exhaustion is pushed farther so that the pressure of the gas is reduced to a fraction of a millimetre of mercury, then the positive glow and the Faraday dark space retreat towards the positive electrode, and the cathode glow also moves in the same direction, and a second dark space, called the Crookes' dark space from the name of its discoverer, makes it appearance next to the cathode, whilst round the cathode a bluish velvety light clings. If the rarefaction of the gas is carried still farther the Crookes' dark space extends until it reaches the anode, and then the glow light disappears and the tube becomes dark, but the glass of which it is made becomes phosphorescent, and if it is ordinary soft soda glass it becomes brilliantly green. In this state the tube is said to have a

high vacuum. This last state is the condition in which the tube creates the X or Röntgen rays.

The phenomena of the glow discharge have always attracted the close attention of the most eminent physicists —Faraday, Spottiswoode and Moulton, Crookes, and J. J Thomson, because they felt that in these effects lay the most probable avenue of approach to a comprehension of the nature of electricity.

Moreover, this scientific study has led to technical applications of great importance.

We see here in a very striking manner the influence of pure scientific research upon electro-technical advances.

About 1872 or 1873 Sir William Crookes began to study experimentally the nature of the electric discharge in gases rarefied to a higher extent than before, and for this purpose, assisted by Charles Gimingham, he greatly improved the Sprengel mercury pump and the technique of making high vacua better than any of the air pumps then used could produce.

Crookes discovered that when the vacuum was so high that the electric discharge produced phosphorescence of the glass, solid objects placed in the bulb or tube in front of the cathode cast a sharp shadow on the glass, preventing within it any phosphorescence. Also that some influence streamed out in straight lines from the cathode which could set in motion small windmills or vanes.

Crookes considered, in opposition to some German physicists, that this influence was "radiant matter" of some kind, and not mere ethereal waves or radiation. This idea was later on brilliantly confirmed by Sir Joseph Thomson by measuring the charge and mass of particles far smaller than chemical atoms which are projected from the cathode. These particles are material in the sense that they have mass as well as a negative electric charge. They are now called electrons, and collectively constitute negative electricity.

The phenomena of the electric glow discharge in a gradually exhausted tube have now been very carefully

studied and are capable of explanation on the assumption that these electrons are shot off with a high velocity from the cathode or negative electrode. When the vacuum is not very high these electrons bombard the atoms of residual gas and produce luminosity or glow in the tube. The mechanism by which this glow is produced is only gradually being made clear.

The view at one time taken of the mechanism of radiation was that when atoms vibrate they create waves of equal period in the ether, just as when a tuning fork vibrates it creates acoustic pressure waves of equal periodic time in the air. This is now known to be erroneous. Professor Niels Bohr suggested that when electrons revolve round an atomic nucleus they can only move in certain paths or orbits, called stationary orbits, in which the movement of the electron does not create radiation. This may seem to be an arbitrary assumption, but such scientific postulates are justified by the degree to which they enable us to predict conclusions from them which are verified by experiment; and this particular hypothesis has been successful in that respect. It appears that the only way in which an electron can disturb the ether and create in it an electric wave is when it suddenly falls back into an atom, which has already been deprived of one of its orbital electrons If the electron before collision has a certain kinetic energy due to its motion then, when it penetrates into an atom's family circle, it takes up some position in it in which it has less energy than before collision. The difference between these two amounts of energy is expended in producing radiation. The next question is as to the frequency or wave length of this radiation. Bohr's second postulate is that the difference between the electron energies is equal to the frequency of the radiation multiplied by a certain constant, called Planck's constant of action.

In a rarefied but ionised gas there are free electrons and ionised positively charged atoms which have lost an electron. Owing to the relatively large free path of an

electron they all acquire by collision with atoms the same mean square velocity of translation, or rather, the squares of these velocities of translation have on an average a certain value determined by the temperature.

When such a vagrant electron strikes an ionised atom it will penetrate down to a certain orbit in which it will rotate with a certain angular energy. The difference between its energy before and after such collision is spent in producing radiation of frequency n such that nh is equal to the difference where h is Planck's constant, and has a numerical value of $6{\cdot}55 \times 10^{-27}$. The frequency of the radiation adjusts itself to this required value.

Since then, corresponding to each orbit K, L, M, etc., there is a definite orbital energy for the electron, it follows that the radiation emitted has certain definite values, and when analysed by a prism exhibits a series of bright lines and not a continuous spectrum.

If the atoms are, however, squeezed tightly together as in a solid, then, owing to the more frequent collisions of the electrons and atoms, the electron energy has all possible values and, therefore, the difference between its energy when free and its energy when taken into an atomic orbit may have an infinite number of values, and thus when the whole radiation is examined by a prism we find a continuous spectrum having every possible wave length in it. This continuous spectrum is characteristic of the radiation of an incandescent solid body. Returning then to the phenomena of the glow discharge. If we provide a long glass tube with wire electrodes sealed into the ends and fill the interior of the tube with some gas at a millimetre or a few millimetres of pressure, and then apply a high voltage to the electrodes either by an induction coil, electric machine or transformer, we observe the following effects as the gas is gradually rarefied to a pressure of about 0·001 of a millimetre.

1. On the surface of the cathode or negative electrode curve there is a bluish glow which clings to the wire or electrode.

2. Around this cathode glow there is a dark space, the Crookes' dark space, the width of which depends upon the gas pressure.

3. Beyond this there is a glow light, called the negative glow.

4. Again, further on there is a well marked dark space, called the Faraday dark space.

5. Then comes a continuous glow which may perhaps be cut up into light and dark layers, called the stratified positive glow. It is from this that the light in the tube chiefly comes, and its colour depends upon the nature of the gas in the tube.

If the gas pressure is reduced, the length of the positive light is reduced also, until at a certain pressure, which is a very small fraction of a millimetre, the Crookes' dark space extends to the positive electrode, and then the walls of the tube become phosphorescent.

As regards the distribution of electric force in the tube, there is a very rapid rise in potential on leaving the cathode, in fact, a large part of the whole voltage required to glow the gas is taken up close to the cathode. In the negative glow there is not much variation or rise in potential, and in the positive column there is a fluctuation of potential and of electric force or space rate of change of potential all along the positive glow.

As regards ionisation of atoms in the tube, research has indicated that the cathode is continually giving off electrons, which may come from the closely adherent layer of gas, these electrons being liberated by the bombardment of the heavy positive atomic ions, which are drawn strongly to the cathode and strike it violently.

These electrons are shot off with great velocity, but owing to their speed they do not produce much ionisation by collision with atoms. This ionisation is more copiously produced by slower moving electrons.

In crossing a London street one's chance of being knocked down by a taxi or bus is very much greater if one moves across slowly than if one crosses quickly. For

the same reason the chance of a quickly moving electron colliding with an atom is less than when the electron is moving slowly.

Hence the Crookes' dark space is a region of quickly moving electrons and its length is about equal to the mean free path of an electron at that gas pressure.

When these electrons lose some of their velocity they begin to ionise the gas and this produces the negative glow. But the electrons so produced draw in more positive gas ions, and this tends to impart a further impulse and quicken up the speed of the electrons. Hence there is a second or Faraday dark space. In the positive glow there is a repetition of this process periodically as we proceed along the tube, the regions of quick moving and slow moving electrons succeeding each other, and these regions of little and much gas ionisation giving us the stratifications of the positive glow.

We can then proceed to consider the application of this glow discharge in electrotechnology.

For a very long time the beautiful effects of the glow discharge in rarefied gases, or so-called vacuum tubes, were hardly more than a scientific curiosity useful for exhibition purposes. When electric lighting began on a large scale and information gathered as to the "efficiency" of various forms of electric lighting by incandescence or arc, in other words, the amount of light or eye-affecting radiation produced by a given expenditure of electric power, reckoned in candles per watt or lumens per watt, it was discovered that the glow discharge had a high luminous efficiency, reckoned in candle-power per watt of electrical power expended on the tube. The first person to make use of this in practical electric lighting was Mr. D. Macfarlane Moore, who, in or before 1906, introduced it in the form of long glass tubes filled with air or carbon dioxide and actuated by an alternating current form and transformer.

The gas was left in the tube at a pressure of 1 or 2 millimetres. The tubes were 2 in. in diameter and 10 to

20 ft. long and required a voltage of 75 volts per foot run to operate them. They gave out a diffused and pleasant light at the rate of 0·6 candle-power per watt. A 20-ft. tube could be made to yield a light of 900 candle-power, and tubes could be run in series up to a length of 200 to 300 ft.

These tubes are run round the ceilings of rooms or tops of cornices. One difficulty with them was the continual tendency of the vacuum to get higher or "harder." To meet this, Macfarlane Moore devised a particular form of valve which admitted a little more air or gas as required. This interior vacuum tube lighting was, however, killed by the advent of the half-watt, gas-filled tungsten wire lamp, which has a higher efficiency, viz., 2 candle-power per watt of electrical power, than the vacuum tube. There is, however, a form of glow light illuminant now very extensively used for advertising purposes, viz., a glass tube filled with rarefied Neon, which has indirect advantages as an illuminant.

Neon is a rare gas which forms about one eighty-thousand part of the atmosphere by bulk. Owing to the large amount of liquid air now produced, it has become a sort of waste product. When caused to glow by an electric discharge the light is characterised by the presence of a number of brilliant red and yellow lines in its spectrum Hence, a tube filled with rarefied neon shines with a bright reddish-yellow light when an electric discharge is passed through it.

Glass tubes filled with neon under a pressure of 7 or 8 millimetres of mercury, can be caused to glow brilliantly by applying to the electrodes an alternating voltage at the rate of 160 to 170 volts per foot length of the tube.

These tubes are made by the Neon Lights Company in two sizes—one, $\frac{7}{16}$ in. in diameter and the other $1\frac{1}{8}$ in. The small sizes require a current of 25 milliamperes to work them, and the large size 300 milliamperes. The light given out is at the rate of 10 candle-power per foot of tube for the small and 45 candle-power for the large size. The

efficiency is approximately 2 candles per watt. This is about the same as the efficiency of the gas-filled tungsten wire lamp These tubes can be bent and fashioned like letters of the alphabet and are extensively used for shop signs

Also, the red light has very considerable fog-penetrating power, and neon tubes are being extensively used as guiding lights to show aeroplanes where to land.

Another use of neon tubes was discovered by the author, viz., as a detector in electric wave meters. Neon has very small dielectric strength for high frequency currents, and a narrow tube filled with rarefied neon glows with a brilliant red light when placed in the field of conductors conveying high frequency electric currents. Suppose a circuit is formed of an inductance in series with a condenser of variable capacity and let a tube of rarefied neon have its electrodes connected to the plates of the condenser. Let the whole arrangement be placed near a circuit in which there is a high frequency. Then an induced current will be produced in the condenser circuit. That current and, therefore, the potential difference between the plates of the condenser will be a maximum when the capacity or inductance is so altered that the natural frequency of the condenser circuit is the same as the frequency of the inducing current

We can tell when the secondary current is a maximum by noticing the brightest glow in a neon tube having its electrodes connected to the terminals of the condenser. In this manner the author made, in 1904, a wave meter, called a cymometer, for measuring wave lengths and frequencies in wireless telegraphy, using a neon tube of spectrum type as a detector of syntony or tuning.

A form of electrical discharge which has great practical importance is that called the *corona* which forms on wires at a high voltage If there be two high-tension circuit wires carrying direct or alternating currents at voltages of 10,000 and upwards, then in the dark these wires are seen, in air at ordinary pressure, to be covered

with a luminous glow called a *corona*. This is caused by an electric discharge taking place into the air. It creates a dissipation of energy as heat and in the case of long high voltage aerial power lines this loss may amount to several kilowatts per mile of circuit.

It depends, however, upon a very large number of factors such as voltage, diameter of the wire, distance of the lead and return wires, moisture, pressure and temperature of the air.

The details and the formulæ predicting the effect of these various factors have been the subject of an immense amount of scientific research.

Much of this has been epitomised in an excellent book entitled "Dielectric Phenomena," by Mr. S. Whitehead, which has been edited by Mr. E. B. Wedmore, Director of the British Electrical and Allied Industries Research Association. In this book is given much valuable information on the electric-spark discharge and on the corona loss in high tension circuits, and it provides striking illustrations of the close connection between pure scientific research and electrical engineering progress.

We have next to consider the form of discharge called the electric arc, and its technical applications.

The great difference between the glow and arc discharge is that in the former the ions, which bestow conductivity and luminosity on the vapour, are formed out of the gaseous medium, and very few come out of the electrodes. Hence the electrodes are not much worn away. In the arc discharge the ions come chiefly out of the electrodes, and these become very hot and are rapidly disintegrated

In order that an arc discharge may take place the source of electromotive force must be capable of furnishing a relatively large current, say, an ampere or more. Hence it must have a comparatively low internal resistance. In forming the arc it is necessary to ionise the gaseous medium initially, either by an electric spark or in some other way. We have generally to bring the electrodes in contact by which they become heated at the

point of contact, and then the cathode begins to emit electrons as in the case of the filament of a thermionic valve. These electrons bombard and ionise the atoms of the vapour produced from the electrodes and the heavy positive ions are drawn back on the cathode and maintain its high temperature and the liberation of electrons. The negative electrons from the vapour in the same way bombard the anode, and positive ions are emitted from it. The peculiar characteristic of the electric arc discharge is that it cannot be maintained unless the cathode is kept hot either by external heating or by ionic bombardment. Accordingly, an arc cannot easily be maintained with a water-cooled metal cathode, but can be maintained with a water-cooled anode and hard carbon cathode. Part of the reason it is difficult to maintain an arc in hydrogen gas is the cooling effect of this gas on the electrodes.

Another special quality of the arc discharge considered as a conductor is that its volt-ampere characteristic curve has a negative slope (see Fig. 27). The explanation of this seems to be somewhat as follows. When the current through the arc is increased, it means that there is a greater rate of delivery of positive ions on the cathode and electrons against the anode, these being derived from the vapour of the arc. These ions and electrons are not taken up into combination as fast as they are delivered, and hence they tend to depress or decrease the potential difference of the electrodes. Accordingly, the potential difference of the electrodes decreases as the current increases, and it is this which gives a characteristic curve with negative slope.

This slope is greater in hydrogen or non-oxygenic gases than in air, the reason being that the oxygen atom seems to have a remarkable power of taking up additional electrons into its outer orbit, there being a natural tendency to complete the number to eight in the outer layers. Hence, if the atmosphere surrounding the arc, formed, say, between carbon electrodes, contains oxygen, these tend to remove the excess of electrons accumulating at

the positive electrode. If, however, we change the surrounding atmosphere to hydrogen, coal gas, or any hydrocarbon, this action does not occur and the characteristic volt-ampere curve becomes steeper (see Fig. 28).

This action is the basis of the operation of the Poulsen

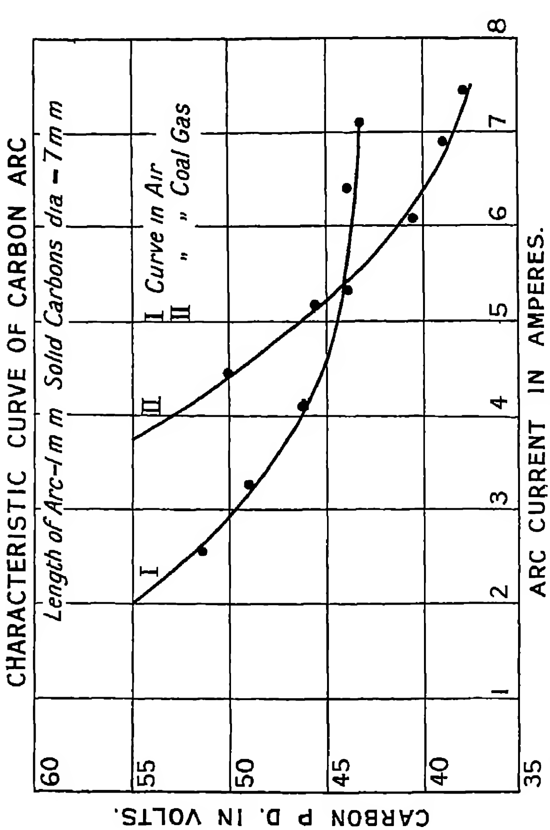


FIG. 27.—Characteristic curves of the electric arc between carbon electrodes in air and in coal gas Vertical distances are the potential difference of the electrodes and horizontal distances the arc currents

arc. As is well-known, the late Mr. Duddell was the first to discover that if a direct current electric arc formed between carbon electrodes was shunted by a condenser in series with a low resistance inductance, electric oscillations are set up in this condenser circuit. The

characteristic curve of a carbon arc in air is, however, not very steep, and hence a condenser of relatively large capacity, say, 1 to 5 microfarads, must be employed to obtain sufficient change in arc current at each oscillation to effect even a small variation in electrode potential differ-

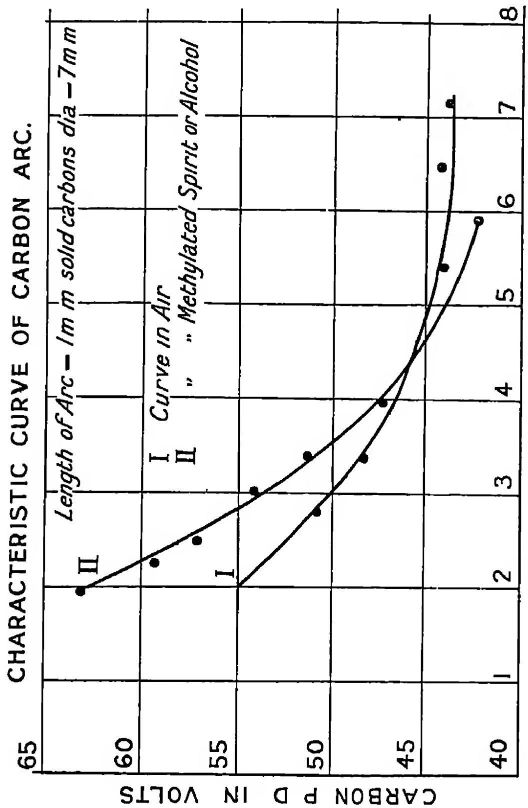


FIG. 28.—Characteristic curves of the electric arc between carbon electrodes in air and in methylated spirit.

ence. That means that the electric oscillations are of rather low frequency and not very large amplitude, and small energy.

V. Poulsen discovered that by forming the arc in a hydrocarbon atmosphere vigorous oscillations could be produced with a much smaller condenser capacity and,

therefore, much higher frequency, and a frequency could then be made sufficiently high and the oscillations vigorous enough to make such an arc useful as a generator of undamped oscillations for use in wireless telegraphy or telephony.

Accordingly, the Poulsen arc became much used for this purpose.

The discovery of the effect of the hydrocarbon vapour on the arc was probably made in the first instance quite empirically, and the reasons for it only discovered later on. We cannot, therefore, consider it to be an instance of pure scientific research leading to technical applications, but only one more illustration that very important inventions or discoveries are frequently stumbled upon by chance, though the casual observation does not yield any fruits unless the observer possesses the necessary knowledge to follow it up with insight and skill.

A technical application of the electric arc discharge of great utility is the production of mercury vapour lamps as illuminants, and mercury arc rectifiers.

The late Mr. Peter Cooper Hewitt, of New York, discovered in 1900 the advantages of an electric arc discharge in mercury vapour as a source of light

A glass or quartz tube has a bulb at one end filled with mercury, and electric connection made therewith by a wire sealed through the glass. At the other end a graphite or iron electrode is connected to a wire sealed through the glass. The tube must be exhausted to a vacuum of less than 0·001 mm. of mercury. If then a direct voltage is applied to the electrodes, but so that the mercury pool is the cathode, and if the tube is then tilted to make the mercury run along it and connect to the anode and then tilted back, a mercury arc discharge forms in the tube, which fills with a brilliant greenish-white light.

This lamp has a high luminous efficiency of about three to four candles per watt, but the light is emitted in the form of a bright line spectrum and very deficient in red rays. Hence it is not suitable as a general illuminant,

but is very rich in ultra-violet light and has, therefore, high photographic and therapeutic power, especially when a quartz tube is employed.

Special starting arrangements for automatic tilting of the tube were at one time employed, but methods for applying a sudden high voltage to ionise a part of the mercury vapour are now employed to start the arc The lamp will not act unless the mercury pool is the cathode, because the high temperature there produced by the bombardment of the mercury by the heavy positive mercury ions is necessary to maintain a supply of mercury vapour to be ionised.

Accordingly, the mercury vapour bulb can act as a rectifier of alternating currents, and in this way has very great utility

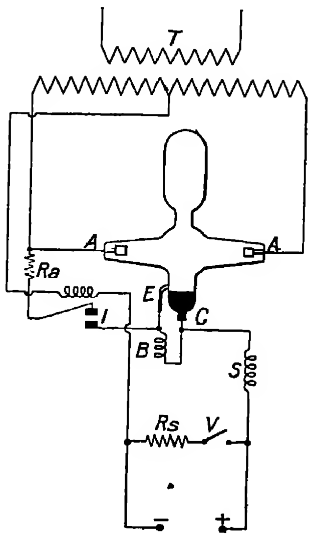


FIG 29 —Cooper-Hewitt mercury rectifier for single-phase alternating currents

When acting as a single-phase rectifier a glass bulb has two lateral prolongations at the ends of which are sealed in graphite anodes (see Fig. 29). At the bottom is a mercury pool as a cathode, and adjacent to it a second small mercury pool, called a starting anode. A transformer T, with middle point connection on the secondary or an autotransformer with the same is necessary. This middle point is connected to the mercury cathode C, and the two outer terminals of the transformer to the two lateral anodes A, A. There is also a connection through a resistance with the starting anode E. The circuit to the mercury cathode is interrupted at one point, and in this gap (— +) is inserted the appliance to be traversed by a direct current, which may be a storage battery, electric arc lamp, or a direct current motor.

The rectifier is started into operation by tilting it so that the mercury slops over from the cathode pool to the starting anode pool, and then the cathode becomes "alive," and the alternating current flows first from one anode and then from the other to the mercury cathode, and then flows back through the direct current apparatus to the middle point of the transformer. In the case of rectification of three-phase alternating currents the bulb has three anodes, set in it at angles of 120 degrees The object of setting these graphite anodes back at the ends of lateral tubes fused into the bulb is to prevent an arc starting from one anode to another.

These rectifiers have many uses as, for instance, in rectifying single-phase or three-phase town supply for the purpose of working direct current projection arc lamps in cinemas or moving pictures.

Although the glass bulb mercury rectifier has been made up to 150 kilowatts capacity by the Hewittic Electric Company, of Hersham, Walton-on-Thames, yet for engineering purposes many engineers desired an all-metal rectifier which would avoid the fragility of a glass bulb. The Brown-Boveri Company, of Baden, Switzerland, accordingly worked out such a rectifier.

It comprises a water-cooled steel cylinder, about a metre diameter and rather more than a metre high. In the bottom of this is the mercury cathode. The lid of this vessel is pierced with six holes for the anodes. The difficulty of making an air-tight, heat-tight gland was overcome by using an asbestos-packed joint made air-tight with mercury The anodes are iron rods insulated through porcelain tubes, which are packed as above described in the lid of the cylinder (see Fig. 30). The three-phase current is supplied from a six-branched secondary, the common point being connected to the mercury cathode through the direct current terminals, and the three pairs of anodes connected to the outside terminals of the three secondary circuits. The anodes

are enclosed in sleeves of metal, the effect of which is to prevent arcing across from anode to anode.

The vacuum is made in the cylinder by a rotary box-pump coupled in series with a mercury condensation pump.

The starting of the arc is effected by means of a separate

FIG 30 —Brown-Boveri all-metal mercury rectifiers with an associated high vacuum air pump for maintaining the necessary high vacuum

single-phase transformer and a starting anode which is placed very near to the mercury cathode surface.

The perfection of the vacuum is tested by an ingenious arrangement.

If a platinum wire is heated by a certain current, and if that wire is in a high vacuum, then it can only lose heat by radiation and conduction from the ends. If, however, the wire is in air, then it loses heat also by convection and, therefore, is not so hot as when in a good vacuum.

Two such wires are employed, one of which is placed in the mercury chamber and the other outside. These two wires form two arms of a Wheatstone's bridge circuit, and the conjugate arms are formed of resistances so adjusted that when a certain heating current of about 150 milliamperes flows through the platinum wires, the bridge is balanced, as shown by a galvanometer, provided one of the wires is in a high vacuum. If that vacuum falls, then

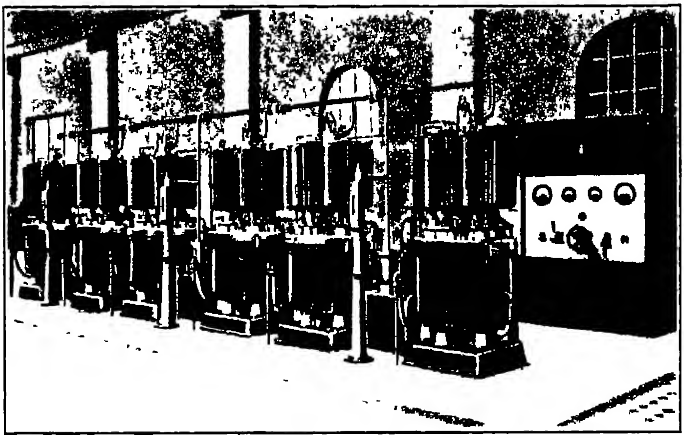


FIG 31 —Brown-Boveri all metal mercury rectifiers for rectifiers for rectifying or changing into a direct current a high voltage alternating current A number of such rectifiers can be worked in parallel.

the bridge is no longer balanced and the bridge galvanometer deflects.

In this way a switchboard instrument was devised which shows at a glance if the vacuum in the mercury vapour chamber is sufficiently good. If not, then the pumps are set in action until the high vacuum is restored

These all-metal mercury rectifiers are now made in sizes up to 500 or 1,000 kw. and for rectifying up to voltages of 5,000 volts or more They are now much used in Switzerland and many other countries for rectifying three-phase alternating currents of a frequency of fifty or so, changing them to direct current for tramway and

electric railway working. The efficiency of transformation is very high—85 to 90 per cent., and a great advantage of these mercury rectifiers is that the efficiency of transformation remains very high, even at quarter or one-fifth of full load. In this respect they have a great advantage over the rotary converter. The mercury arc rectifiers can be worked in parallel so as to deal with large powers (see Fig. 31).

There is little or no consumption of mercury and no renewals necessary except change in the iron anodes.

It is curious to note that the electric arc is capable of acting in a duplex manner In the case of the Poulsen arc, we make use of it to convert direct current into high frequency alternating current.

In the mercury arc rectifier we make use of the arc to convert a low frequency alternating current into a direct current.

As a public illuminant, the carbon electric arc, in all its forms, has been killed by the advent of the large gas-filled glow lamp, and the chief use of it now is as a source of of light in searchlights and cinema projectors, and in optical lanterns and in lighthouses.

Nevertheless, the improvements made in the production of the carbon electrodes for such technical purposes have reacted on scientific research by providing us with our most intense source of light for optical purposes.

We shall consider the uses of the electric arc in various forms of electric heating in Chapter VII.

CHAPTER V

TELEPHONY

In hardly any other branch of electro-technical work is the close inter-connection of pure scientific research and practical achievement better seen than in the labours which have given us the means of transmitting human speech and music over vast distances both with and without wires.

The possibility of this transmission was foreseen long before it was actually accomplished.

In spite of much early work, such as that of Philip Reiss, the verdict of Courts of Law after prolonged litigation was, that Alexander Graham Bell was the first to devise the means for this electric transmission of speech along a telegraph wire.

He was the son of Alexander Melville Bell, who was at one time, about 1866, lecturer on Elocution at University College, London, and his celebrated son was a contemporary student with the author of this book, at University College (1866–68). Mr. Bell, Senior, had devised a method of visible speech for assisting the deaf, and Graham Bell, therefore, had his attention early turned to the subject of phonetics. Mr. Bell emigrated to Canada in 1870, and, before long, Alexander Graham Bell had his thoughts directed to the problem of multiple telegraphy, and he invented a type of transmitter which enabled musical tones of various frequency to be transmitted simultaneously and electrically along a wire and separated out at the receiving end. Part of this apparatus involved a set of vibrating steel reeds, caused to oscillate electro-magnets. The intermittent electric currents sent along the line to energise these magnets was obtained by the

interruption of a circuit by a similar reed at the transmitting end.

On one occasion, almost by an accident, imperfect speech sounds were transmitted, and Bell set himself earnestly to work to discover the conditions. Finally, he solved the problem by the invention of the magneto-telephone which acted, not only as a transmitter, but as a receiver.

In its final form the Bell telephone consisted of a bar or horseshoe steel magnet, on the poles of which were soft iron pieces, and round these pole pieces coils of insulated wire were wound (see Figs. 32 and 34). A thin steel disk, or diaphragm, about 2¼ inches in diameter was fixed with its centre near the magnet pole pieces but not quite touching them. The same type of instrument was used as a transmitter and receiver.

Bell realised that the fundamental condition for electric speech transmission was that the circuit must never be broken, but that the current in it must fluctuate just in proportion to the change in air pressure near the diaphragm of the receiver. In his system the change in air pressure, due to speech sounds made close to the diaphragm of the transmitter, caused movements of it which changed the magnetic flux passing through the wire coil of the telephone, and this created an induced current nearly proportional to the rate of change of this flux This current was sent into the line, and at the receiving end caused a variation in strength of the pole of the magnet of the receiver telephone, and this again set in vibration the diaphragm and reproduced the speech sounds by causing changes of air pressure near to it.

When we consider this complicated series of physical operations and the want of strict proportionality between the effect and the cause at each stage, the truly astonishing thing was that Bell's magneto telephone transmitted speech at all Nevertheless, it did do so, and it was exhibited at the Centennial Exhibition at Philadelphia, in 1876, where the late Lord Kelvin tried it, and the

same year described enthusiastically its performance to section A of the British Association, which met that year in Glasgow.

Bell's invention realised in the highest possible degree mathematical symmetry and the principle of reversibility. There was the line wire in the centre, the two coils of insulated wire round the poles of the two permanent magnets at both ends, the two diaphragms close to the magnet poles, and the two gossips with their mouths or ears close to the diaphragms (see Fig. 32). Identical instruments functioned as transmitter and receiver. The Bell magneto telephone was, however, an

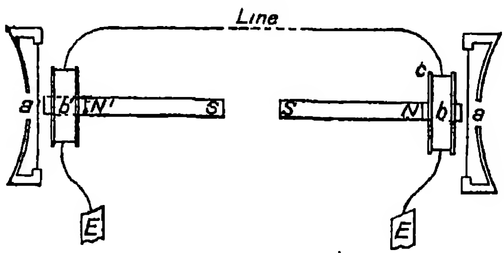


FIG 32 —Bell's telephones acting as transmitter and receiver. NS, permanent magnet, *bb'*, coils of wire, *a*, steel diaphragm.

imperfect transmitter, because the energy of the current put into the line was derived merely from a part of the energy of the aerial vibrations made near the diaphragm by the speech sounds, and that is extremely small. Before the telephone, therefore, could become a commercial instrument it was necessary to find some means of causing speech sounds to modulate the strength of a strong electric current produced by a battery or other separate external generator. This was done by Edison and Hughes and their followers in the invention and improvement of the microphone transmitter.

Edison had already discovered, in 1878, that a button of lampblack varied its electrical resistance remarkably when slightly compressed, and he had constructed an

instrument he called a micro-tasimeter which enabled him to detect very small expansions of metal rods.* In 1878 he applied this to construct a telephone transmitter by making the motions of a metal diaphragm moved by speech-sound air pressure changes compress more or less the carbon button. He thus caused speech sounds to modulate the current from a battery, and made his carbon button transmitter, which proved to be, to a certain extent, a practical solution, though an imperfect one, of the problem.

The position then was that Bell's magneto instrument was an effective receiver or could convert back electric current energy to sound wave energy; Edison had an effective transmitter which could operate in the reverse direction The problem was then attacked in turn by Professor D. E. Hughes from a rather different angle. He had noticed that Bell's receiver was extraordinarily sensitive to sudden changes of current through it, and he found that if in any part of the circuit there was a loose contact, very slight vibrations of it, even those produced by air waves, could create sounds in the telephone receiver.

He laid two pieces of graphitic carbon loosely on each other and inserted this contact with a battery in series, with a Bell telephone.

He found that speech made near the loose contact was reproduced by the Bell telephone. He called this device a *microphone.* Hughes' experiments were described to the Royal Society, in May, 1878, and resulted in a vigorous controversy with Edison, who considered his ideas had been appropriated. Apart from these side issues Hughes' experiments threw much light on the subject of loose or microphonic contacts, and the result was that the practical telephone transmitter was developed out of a form of microphone contact formed with granules of graphitic carbon enclosed between a solid metal back and a metal diaphragm set in vibration by speech sounds. The

* See *The Telegraphic Journal,* August 1st, 1878, Vol. 6, p 314

combination of this carbon microphone transmitter, first in the form devised by Blake, later by White, and the Bell telephone receiver, gave us the practical working telephone of the present day (see Figs. 33 and 34).

Since the changes of air pressure made by the speech

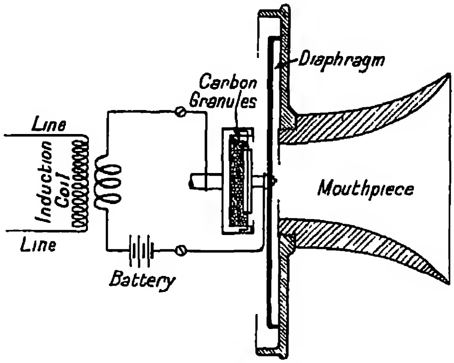


FIG 33 —Section of a carbon granule telephone transmitter

sounds near to the diaphragm of the transmitter only make small changes in the resistance of the carbon granules, which is generally an increase in resistance due to diminution of contact of the diaphragm and the granules, it is necessary to connect the battery providing

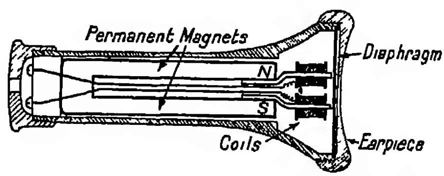


FIG 34 —Section of modern bell magneto telephone receiver

the current and the carbon granules in series with one coil of low resistance of an induction coil, the secondary or high resistance circuit of the latter being connected to the Bell receiver (see Fig. 35).

Small changes in the resistance of the microphone or transmitter can then make relatively large changes in the

current in the primary of the induction coil and also in the Bell receiver.

The remarkable fact about the whole device is its extraordinary inefficiency from an energy-transforming point of view, and the manner in which the trained human ear is able to guess from a mere caricature of the original speech wave form as reproduced at the receiving end, the intellectual meaning of the sound conveyed.

An enormous amount of pure scientific research has been carried out of late years on the dynamics of speech sounds and the analysis of them and effect of all parts of the telephone appliances and of the line on the wave form of the transmitted currents and reproduced air vibrations.

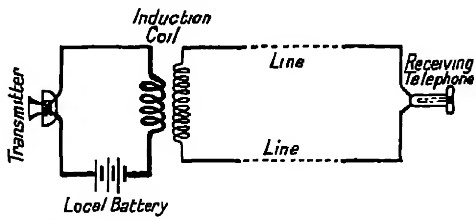


FIG. 35.—The arrangement of an induction coil interposed between transmitter and receiver

Much of this has of late come to us from the United States, from the research laboratories of the Western Electric, the American Telephone or Telegraph and Bell Telephone Companies Much, however, of the fundamental scientific work was done in Great Britain and had its origin there If we have at all fallen behind, it is not due to want of scientific ability or originality, but to the superior instrumental equipment in U.S A.

A very few of the results of this scientific work may here be mentioned.

When a sound wave passes through the air there is a rapid change of air pressure at each point above and below the normal For speech sounds the frequency of these pressure changes lie between 100 and 6,000, but good quality of speech can be transmitted by telephone over a

range of 100 to 2,500. Perfect speech of all kinds covers a range of 100 to 8,000, and music 100 to 10,000. The ear is most sensitive to frequencies of about 1,000 to 2,000, and 800 is often taken as an average telephonic frequency.

The minimum audible sound for a good human ear at 1,000 frequency requires an R M.S. value of the pressure change to be 0·15 dyne per square centimetre of area. It may be noted that a *dyne* is a unit of force on the metric system and is equal to about one-thousandth part of the weight of one gramme.

The amplitude of motion of the air particle when this minimum audible sound is being produced is very small, not much more than 8 to 10 $\times$ 10^{-8} cm, about five or ten times the diameter of an atom of gas (R.M.S. stands for the square root of the mean of the squares of the quantity). When one is speaking in an ordinary conversational tone the R.M S. value of the air pressure change 1 in. from the mouth is about 11 dynes per square centimetre, and the energy passing out about 3 ergs per square centimetre. Hence, when speaking to an ordinary telephone microphone mouthpiece one is expending power equal to about 100 ergs per second on the diaphragm. This is a power equal to $\frac{1}{100000}$ of a *watt*.

Measurements made by Kennelly and Affel, and by Louis V. King, on the acoustic efficiency of a Bell telephone show that even at resonance frequency it hardly converts more than 1 per cent. of the electric current power given to it into sound wave power in the air near the diaphragm, and at frequency far removed from resonance, not much more than $\frac{1}{100}$ of 1 per cent.

Accordingly, it is seen that the Bell arrangement in which the same instrument is both transmitter, a receiver has an extraordinarily small energy transformation efficiency.

It is remarkable, however, that in fifty years we have not been able to depart in principle from Bell's invention in the type of receiver used in commercial telephones. Edison invented, in 1879, as an alternative device his chalk

cylinder receiver, which was based on the fact that the friction between a metal and certain non-metal substances is altered when a potential difference is made between them.

This was revived in another form with an agate cylinder, in 1921, by Messrs. Rahbek and Johnson, but Mr. Rollo Appleyard had previously discovered, in 1905, the adhesion of a metal plate to a dielectric when a potential difference was made between them.

Dealing then with the problem of the transmitting line, the earliest experience with the telephone showed the great influence of it and that intelligible telephony was only practical through a very few miles of submarine or subterranean cable. At that time very crude theories were held concerning telephonic transmission. The mistake was made of supposing that the theory of the transmission of slow telegraphic signals through a cable, which had been worked out by Lord Kelvin in 1855, would apply to telephone transmission, and erroneous empirical rules were deduced The late Mr. Oliver Heaviside was the first to deal with the problem mathematically with sufficient knowledge. He showed, in 1887, that when an electric wave of complex wave form travels along a telephone wire, the higher harmonics into which the wave form can be resolved attenuate or die out more quickly than the lower or fundamental wave. Also they travel more quickly. Hence results a *distortion* of the wave form. He proved that this could be prevented by increasing the inductance of the cable per mile to the point that it becomes equal to the product of the capacity, copper resistance, and insulation resistance of the line, all per mile or naut or unit of length.

He had some difficulty in bringing this home to so-called practical telephonists, who had generally regarded inductance in the line as an obstacle to telephony. The late Professor Silvanus Thompson also saw that the capacity of the line was the true enemy and could only be overcome by adding inductance or reducing insulation

resistance. No attempts were made to put these correct theories into practice until Professor I Pupin, in U S.A., in 1899 and 1900, published two masterly papers on the subject, in which he showed the benefits which could be obtained by "loading" a telephone cable at intervals with inductance coils spaced according to a certain rule (see Fig. 36).

The mathematical problem is very similar to that of the theory of the vibrations of a string loaded with weights at equal distances, which had been solved by the French mathematician, Lagrange, at the beginning of the nineteenth century. Pupin showed that if the inductance coils were spaced at such intervals that the wave of current in the line extended over a length equal to eight

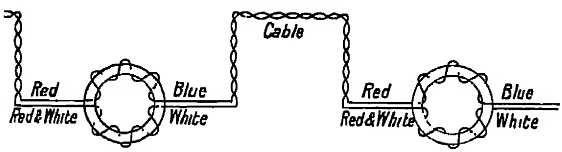


FIG 36—Pupin's method of loading a telephone cable by insertion of inductance coils at intervals in the circuit

or nine times the intercoil distance, then the line acted as if the inductance was uniformly distributed over it.

It was, therefore, easy to give the line any required inductance by means of toroidal coils having a divided iron core (see Fig. 37).

The inductance of an unloaded line may be taken at about 1 millihenry per mile, but by coils spaced one to two miles apart it is quite easy to raise it to 100 millihenrys per mile. Although this, in general, is not enough to satisfy Heaviside's rule for a distortionless cable, it is of considerable utility, and the result of Pupin's work was that telephone lines everywhere began to be coil loaded with marked improvement and about doubling the range for good telephony.

It was not until a little later that Krarap, in Denmark, made suggestions for uniform loading by over-winding

the copper wire with a single layer of iron wire in closely adjacent turns as a means of increasing inductance. It is

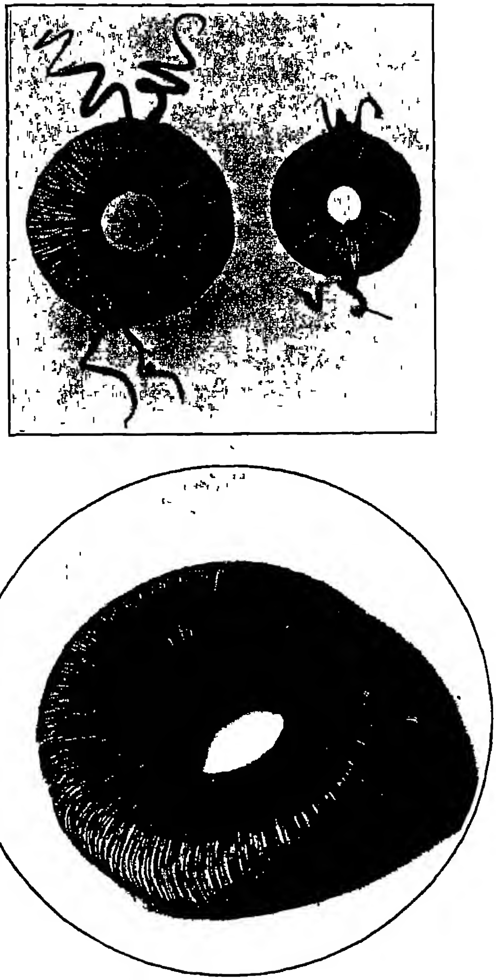


Fig 37.—Pupin inductance coils formed with two windings of insulated wire on a ring-shaped core of laminated iron.

not possible in this way to increase the inductance as much as by coil loading without increasing also capacity

and effective line resistance. As long as the over-winding is done with iron wire the safe limits of inductance increase is far less than with coil loading, perhaps not one-tenth of the latter.

Mention has been made in Chapter II. of the extraordinary qualities of the nickel-iron alloy, consisting of 21·5 per cent. of iron and 78·5 per cent. of nickel. It has been found that its magnetic permeability for very small magnetic forces, say, 0·05 c.g s. unit, is nearly 1,000 times that of iron under the same force.

The remarkable thing is that for large forces or flux densities of, say, 10,000 to 12,000 B , the permeability of this alloy (called *permalloy*) is not greater than that of pure soft iron. It seems as if Nature had prepared for us a material having exactly the qualities required for the uniform loading of telephone cables, especially submarine telephone cables. And not only so, but for submarine telegraph cables it is equally an improvement, and is able to increase the speed of sending by syphon recorder signals to ten times that through an equal copper unloaded cable. It must not be assumed, however, that the advantages of permalloy for submarine telegraph cable loading is an obvious corollary of its advantages for telephone cable loading. The electric processes going on in the two cables are quite different. In the case of the telephone line we require to propagate along it with unchanged wave form a set of electric waves of current, and the condition to be fulfilled is that these waves must be propagated with all the harmonic constituents equally attenuated and with the same speed. Analysis shows that this will be achieved if the inductance of the line complies with conditions mentioned above. In the case of a submarine cable the requirement is speed of transmission of signals. This does not mean that the currents are to travel more quickly, but that the signals (dot dash) made by reversing the direction of current in the line shall be able to follow each other more quickly. In a submarine cable of ordinary unloaded type, when the key is put down at the

sending end the current at the receiving end rises up very slowly according to a " curve of arrival." If then we send, say, a " dot " by a tap on the sending key, we cannot send another " dot " or a " dash " or reversed current until the first dot current has risen up to such a strength as to affect sufficiently the receiving recorder. If we send the " dash " too soon it simply wipes out the " dot " and nothing is received. The full theory of this was given by Lord Kelvin, in 1885. If, however, the cable is sufficiently loaded with inductance this retards the rise of current, but causes it to persist when once established. The effect is that a sudden closing of the sending key causes a wave of current along the cable, which has a very steep wave front, and as soon as this has passed through the receiving instrument we can send another wave with current either in the same or reverse direction. The result is to quicken up the rate at which jerks of current, one way or the other, can be got through the receiving recorder, and this accelerates the speed of signalling although it retards the rate at which the current wave travels along the cable (see Fig. 38).

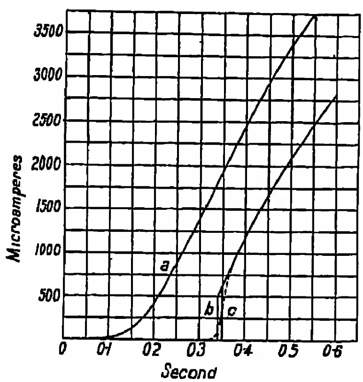


Fig 38.—Curves of arrival on long submarine telegraph cable 0a is the curve on an unloaded cable and shows the mode in which the received current increases with time b and c are curves on loaded cables

A very large amount of research has been carried out in the United States on the effect of mechanical strain and time on the magnetic qualities of the nickel-iron alloys of various composition.

The very interesting fact has been noted that large hysteresis is not a necessary accompaniment of large or high ferromagnetic qualities.

Thus, in iron at a high flux density, say, B = 15,000, the hysteresis loss may be, say, 6,500 ergs per cycle per centimetre length of a certain size of wire.

For permalloy, with 21·5 per cent. iron, 78·5 per cent. nickel, the hysteresis for same size and for B = 11,000, was found to be only 80 ergs or $\frac{1}{80}$th part of that of iron. This shows that magnetic hysteresis is a secondary effect and not necessarily connected with high permeability under low magnetising forces. The result of all this important research work has been to extend enormously the effective range of commercial telephony, and to make possible increased sending speed through submarine cables and underground lines to an extent quite out of the question before.

Already we have begun to see the revolutionising effect of this discovery of permalloy on transatlantic telegraphy.

The Standard Telephones and Cables Company, Ltd , formerly called the Western Union Telegraph Company have laid, during 1926, a permalloy continuously loaded submarine cable between Sennen, at Land's End, in Cornwall, England, and Bay Roberts, in U S.A. The cost of this cable has been £1,250,000. This chrome permalloy cable is the first loaded transatlantic cable

The total length is 3,300 nautical miles, and it weighs altogether 11,700 tons. The cable has attained a speed of transmission of 2,500 letters per minute as compared with 280 letters per minute on the previous unloaded cable. A second Pacific loaded cable is also being laid.

A word or two must then be said on two other improvements, which are the outcome of much large-scale research, viz , the dry core telephone cable and the phantom method of increasing the carrying power of telephone cables. The early telephone work was carried out with aerial wires, but when these increased in number the public demanded that the wires should be put out of sight and underground. The first attempts to use gutta-percha or india-rubber covered wires for this purpose showed the enormous influence of the insulating material in

increasing line capacity and so reducing telephonic range and clearness. Hence, after much experimenting the loose paper insulation or dry core with lead covering drawn over it was devised. At the present time telephone wires (lead and return) are covered with a loose twist of dry paper (the air being the real dielectric), and these are twisted tightly together. Pairs of pairs are then twisted to make a "quad," and each pair is a separate circuit. But we can make a third or phantom circuit by using one pair as the lead and the other as the return. Also, under some circumstances, it is possible to make a second phantom circuit by using all four wires as a lead and the sheath or earth as a return (see Fig. 39).

These phantom circuits can also be loaded by appropriate inductance coils.

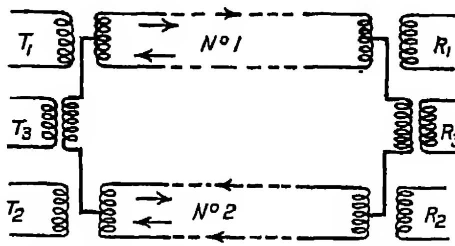


FIG. 39.—A phantom telephone circuit formed out of two independent circuits No 1 and No. 2, each with its own transmitter T and receiver R The phantom circuit is formed by using the two wires of No 1 and No. 2 circuit as lead and return for a third speaking circuit T_3, R_3.

A practical problem of great importance in connection with telephony has been the production of a satisfactory telephone relay or repeater which should repeat the attenuated telephone currents with augmented energy on to a second connected line. Immense ingenuity has been brought to bear on this problem, but until the advent of the thermionic valve nothing was produced which thoroughly satisfied telephonic engineers. Attention was directed in the third chapter to the scientific work which resulted in the production of the three-electrode amplifying valve It was there explained that slight variations of grid potential are capable of controlling and varying in exactly the same manner the electron stream from filament to plate or anode, pro-

vided we work on the straight part of the characteristic curve.

When, then, the true scientific theory of the thermionic amplifier had been worked out, it became at once evident that we had in it the long desired telephone relay. If we connect a suitable two-coil transformer to the grid and filament and another to the filament and plate, it is clear that a feeble fluctuating or telephonic current passing through the primary of the grid transformer, will cause an augmented but exactly similar current to appear in the secondary of the plate transformer, and a feeble telephonic current can, therefore, be repeated as a stronger one on to a second line (see Fig. 40).

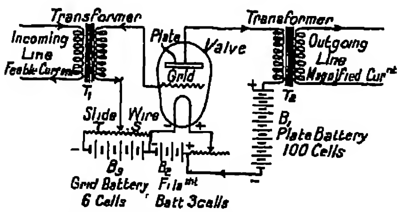


FIG 40.—A thermionic valve used as a one-way telephone repeater to connect two lines and amplify the speech currents from one line to the other

A telephone relay has, however, to operate in both directions, and for this purpose it was necessary to associate with the thermionic amplifier a circuit called an Edison relay circuit.

The nature of it will be understood from the diagram in Figs. 41 and 42.

The enormous advantage of this thermionic relay is that it enables much less costly copper conductors to be used. We can employ a smaller size of wire and then compensate for the attenuation caused by the higher resistance by boosting up the attenuated currents by a thermionic relay.

These repeater stations are now established on the G.P.O. telephone trunk lines in considerable numbers. Thus the London to Glasgow main underground loaded trunk lines are run with 20 or 40 lb. per mile conductors, but there are nine repeater stations on the way—London, Fenny Stratford, Derby, Leeds, Catterick, Newcastle,

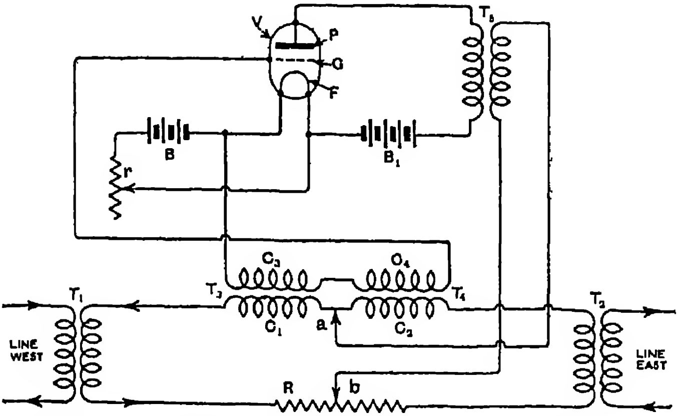


FIG. 41.—An Edison circuit for employing a single thermionic valve as a two-way telephone repeater for one line (west) to another line (east) An intermediate circuit is employed and connections so made that the valve cannot excite self-oscillations.

Jedburgh, Edinburgh, and Glasgow. If this line had to be run without repeaters, then to secure the same attenuation and telephonic efficiency it would be necessary to use copper wire from ten to twenty times the thickness, and, therefore, cost, of the copper now used in the lines.

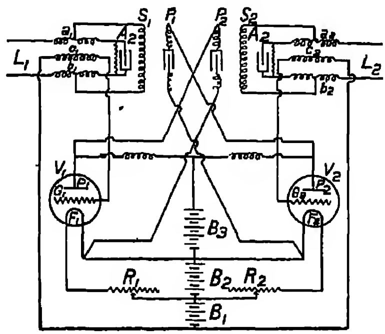


FIG. 42 —A practical two-way repeater circuit, using two thermionic valves V_1 and V_2 and artificial lines A_2 A_2 to balance the actual lines so that the repeater station need not be in the centre of the line

These repeater stations for the above-named line, are equipped with 1,350 repeaters, employing 3,632 thermionic amplifiers. These last are the oxide-coated metallic filament type of valve described in Chapter III., as made by the Western Electric Company, now called the Standard Telephones and Cables Company.

Not only has the thermionic valve and the scientific

researches which led to its evolution given us a telephonic relay of such a perfect kind that it has made all other forms obsolete, but the same appliance used in a different way has enabled us to solve another practical problem, viz., that of multiple telephony or transmitting several telephonic messages along a single wire. The problem of multiple telegraphy was solved long ago by the invention of such telegraphic appliances as the Baudôt and Murray multiplex, and also the quadruplex transmission. Multiple telephony has been accomplished by the use of the modulating thermionic valve.

It has already been pointed out that the characteristic

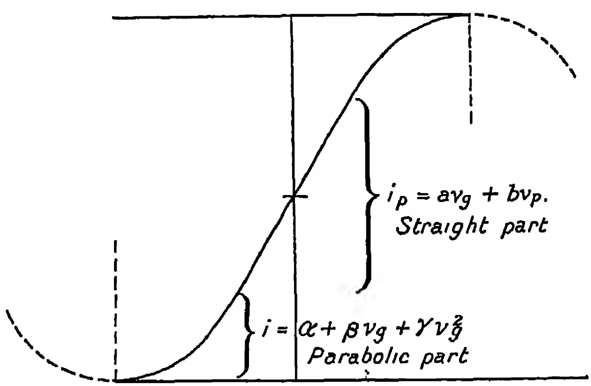


FIG. 43.—Characteristic curve of a three-electrode thermionic valve showing the straight and parabolic portions.

curve of the thermionic valve or curve connecting grid voltage to plate current is a curious S-shaped curve, which can nearly be represented by a straight line joining two semiparabolas. No one has been able to obtain an equation which denotes the whole curve, but the parabolic parts are nearly represented by the equation:

$$i = a + bv + cv^2 \text{ (see Fig. 43).}$$

If then we give the grid such a bias or voltage as to work on the straight part, the variations of plate current are a *copy* of the variations of grid voltage. But if we work on the *curved* part it is not so.

If we make the grid variations to consist of simultaneous *low* and *high* frequency fluctuations following a sine curve law, or if $v = V_1 \sin pt + V_2 \sin qt$, where $p = 2\pi n$, $q = 2\pi m$, then on putting this value of v in $i = a + bv + cv^2$, we have a complex plate current

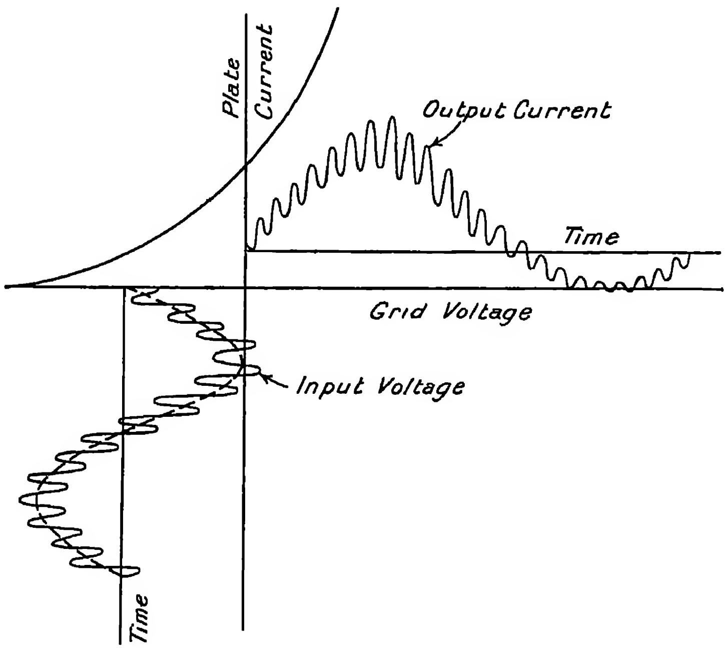
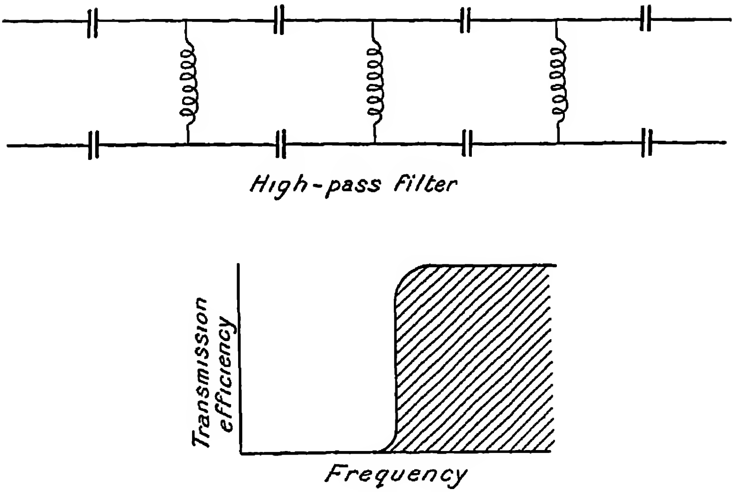


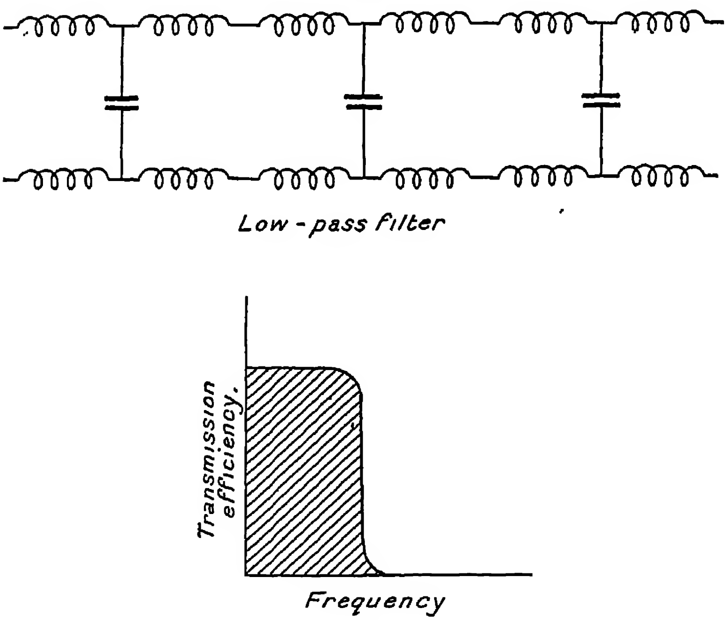
FIG 44.—A diagram showing that when we are impressing high and low frequencies on the grid of a thermionic valve at a point on the curved part of the characteristic the output or anode current variation is not a copy of the grid potential variation.

expression which contains terms in $\sin pt$, $\sin qt$, $\sin^2 pt$, $\sin^2 qt$, $\sin pt \sin qt$, or frequencies p, q, $2p$, $2q$, $p + q$, and $p-q$.
Since $\sin pt \sin qt = \frac{1}{2} \{\cos (p - q)t - \cos (p + q)t\}$ and $\sin {}^2pt = \frac{1}{2} - \frac{1}{2} \cos 2pt$.

Hence, the plate current is not a copy of the grid voltage, but is said to be *modulated* (see Fig. 44).

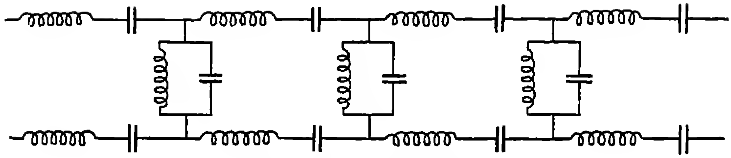

High-pass filter
Transmission efficiency
Frequency

(a)

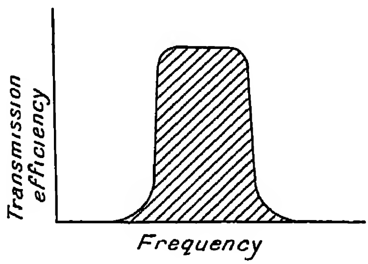

Low-pass filter
Transmission efficiency.
Frequency

(b)

Fig. 45.



Band-pass Filter



(c)

FIG. 45.

It is necessary to explain next what is meant by a wave-filter.

It is a kind of artificial telephone line built up of condensers and of inductive resistances arranged in a certain way, which permits the propagation along it :

(i.) Of only high frequency current, called a high pass filter.

(ii.) Of only low frequency or speech currents, called a low pass filter.

(iii.) Of a certain narrow range of frequencies, called a band filter.

The arrangements for the three kinds will be understood from the diagrams in Fig. 45 *a*, *b*, *c*, in which the two short parallel lines stand for a condenser and the little curls for inductive resistances.

The study of the construction of these filters has been a most important element in perfecting carrier wave telephony.

Returning then to our modulating valve. Suppose we impress upon the grid oscillations of two frequencies, first,

a high-frequency oscillation, say, 10,000 per second, then our p in the above formulæ denotes $2\pi \times 10,000$, where $\pi = 3{\cdot}1415$, and suppose we also superimpose a low frequency, called an audio-frequency lying between, say, 100 and 2,000. Then q denotes $2\pi \times (100 \text{ to } 2,000)$. This we can do by means of two transformers (H.F.) and (L.F.) inserted in the grid circuit of the valve (see Fig. 46).

The first is called the carrier wave frequency and the second the speech frequency. It must be understood

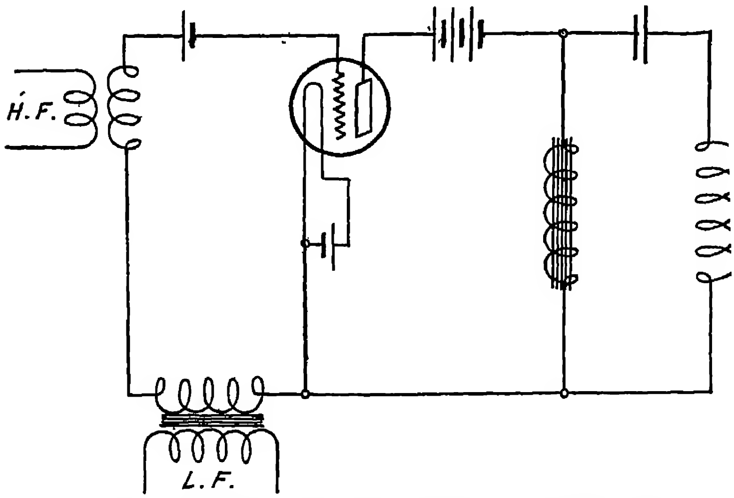


FIG. 46.—A diagram showing the manner of impressing on the grid circuit of a thermionic valve oscillations of potential of two frequencies high and low.

that this last may be anything between 100 and 2,000. Let us consider a single speech frequency of, say, 1,000.

Then we are impressing on the grid of the valve two frequencies, viz., 10,000 and 1,000. Hence, from the above explanations it will be seen that in the modulated anode current of the valve we have oscillations of frequencies, $10,000 + 1,000$, $10,000 - 1,000$, 10,000, 1,000, 2,000, 20,000, etc. We can, by suitable wave filters, separate out and stop all frequencies but the 11,000 and the 10,000.

We can transmit these high frequency currents along a telephone line without interfering with other low-frequency currents, and then at the receiving end we can impress these upon the grid of another valve, called a demodulating valve, and obtain currents of frequency equal to the sum or difference of 11,000 and 10,000, viz, 21,000 and 1,000. We can filter off the high-frequency and recover the low, or speech-frequency currents. In this way we can convey speech currents along a telephone line not in the form of low-frequency speech currents but in the form of a *band* or range of high-frequency currents.

By the use of a selection of carrier frequencies, such that the separate bands do not overlap, we can convey several different sets of speech currents for telephone working simultaneously along a single line, and what is more important, send them along a telegraph line which is being simultaneously used for telegraph working.

Thus a single line from New York to Chicago conveys at one moment forty telegraph messages each way, or eighty duplexed and five telephone messages, or eighty-five distinct communications in all.

Space will not permit any lengthy reference to the manifold scientific researches which have brought wireless or radio-telephony to its present perfection and given us the wonderful and popular broadcasting. It is the outcome of the extensive scientific study that has been made of the Bell or magneto receiving telephone, and of the devices for modulating, by means of the extremely slight pressure variations in the air produced by human speech, another stronger current. These devices are collectively called microphones. The difficulty has always been to modulate a sufficiently large electric current without distortion.

This, however, has now been perfectly accomplished by the thermionic amplifying valve. Especial attention has had to be paid to the transmitting microphone. The variable resistance microphone with its diaphragm having

one very pronounced resonance frequency has been found unsuitable.

It is essential that the movable part of the instrument which is affected by voice waves shall either be aperiodic or else have a very high resonance frequency far above that of the highest harmonic present in music or human speech.

In one form, a flat, close-wound spiral of aluminium wire is floated in a strong magnetic field of such form that very small movements of the spiral cause an induced E.M.F. in it. These movements are created by the voice waves.

These motions in the strong magnetic field create an induced E.M.F., which is amplified by thermionic valves, and then employed to modulate the amplitude of the high-frequency carrier waves sent out from the broadcasting stations, so as to superimpose on the carrier wave of radio-frequency a pulsation of audio-frequency, which conveys the speech or music sounds. Everyone is aware of the wonderful manner in which the broadcasting now conveys the quality of speech so that we become familiar with the very tones and accents of certain speakers, and this is due to the faithfulness with which the vibrating part of the microphone takes up all the small higher harmonics in the wave of the incident sound. Similarly, great research has been given to the improvement of various types of loud-speaking telephone for reception, both with horn and hornless. The best specimens of both types give a fairly good reproduction of speech and music, but there is room for improvement.

The chief desideratum is to get rid of any natural frequency in the diaphragm or pronounced resonance in the horn.

In hearing music with which one is not familiar the defects due to these causes are not much noticed, and in hearing speech the human ear does a deal of guessing, so that the sense is made out even if certain consonants, such as sibilants and fricatives are badly reproduced. If, however, we hear by wireless a simple but melodious

air played with which we are familiar, the limitations of the loud-speaker as regards reproduction are soon noticed. When once an article comes in demand commercially on a large scale it is worth while to spend much in research for improvements, and that is often a question of money. Hence we have every confidence in the continued improvement of the loud-speaking telephone.

There are many departments of technical work in which the research necessary can only be conducted by the combined labours of many persons, and in which the large scale observations necessary are expensive to carry out.

A good example of this is the complicated phenomena which present themselves in long distance radio telegraphy or telephony owing to the ionisation of the terrestrial atmosphere and the nature of the terrestrial surface over which transmission takes place.

In very early days of wireless telegraphy it was noticed that the rather short waves then used, about 1,000 feet in wave length, travelled better over sea than land, and that over some land surfaces transmission was very difficult, whilst the effect of cliffs and hills in casting "wireless shadows" was investigated, especially by Admiral Sir Henry Jackson. In 1902, Senator Marconi made the discovery that long electric waves travelled nearly twice as far over the Atlantic Ocean by night than by day before being weakened to the point of non-detection.

This was at once recognised to be, in some way, due to atmospheric ionisation. Even a year before that time, the fact that such waves sent out from Poldhu were detectable in Newfoundland had excited some surprise in the minds of physicists (especially the late Lord Rayleigh) unable to reconcile it with ordinary wave propagation.

Since that time an immense amount of research has led generally to the conclusion that, at a height of 60 to 100 kilometres above the earth's surface there must be a heavily ionised layer of atmospheric gases. The

effect of sunlight by day must be to extend this to a lower level.

The phenomena of the Aurora and atmospheric electricity, as well as the changes in terrestrial magnetic force by day, all agree in support of this conclusion.

The daily experience at present that comparatively short electric waves can travel to the antipodes is a complete proof that powerful factors, other than diffraction, are operative in wireless wave propagation round the earth. It shows that some conditions are present which bestow a greater velocity on the electric waves at higher than at lower levels in the atmosphere, and this means that the effective dielectric constant of the medium must be less at a great height. A recent theoretical discussion of the problem by Sir Joseph Larmor has shed fresh light on it. At very great heights, where the atmosphere is very much rarefied and ionised, the mean free path of an ion may be several centimetres long. As an electric wave passes over it, the ion is moved to and fro by the electric force. If the ion collides with a molecule during the passage of the wave, energy is dissipated and the medium becomes, as it were, more or less opaque to the waves. If the mean free path is long, the ions are displaced to and fro, and the result is that the effective electric strain for a given impressed electric stress is diminished. Hence the dielectric constant is decreased and the wave velocity increased. There must, however, be nothing which causes dissipation of energy or else there will be a rapid attenuation of wave amplitude. It is well known that Senator Marconi has bestowed much attention of late years to short-wave propagation, and in conjunction with Mr. C. S. Franklin, has achieved great success with it.

In October, 1924, Marconi discovered that the daylight range of wireless telegraphy increased very rapidly as the wave length was reduced from 100 to 32 metres, and that perfect communication could be established at all hours of the day and night between England and

Australia with the 32-metre wave, using only 10 to 12 kw. in the transmitter.

The exploration for the full reasons of all the complicated variations of wireless transmission with different wave lengths, and at different times of the day and year, will occupy investigators yet for many years, and even the briefest summary of that which has been learnt is all that can be given now.

The question of the cause and nature of atmospheric disturbances or vagrant electric waves has occupied much attention. Important scientific researches by Professor E. V. Appleton and Mr. R. A. Watson Watt, have employed a cathode ray tube to delineate optically and give absolute values of the fields produced by these waves. They find that there are two classes of them: "aperiodic" or damped, and "quasi-periodic," or oscillatory to a small extent, comprising, perhaps, one complete period. The aperiodic endure, on an average, one-thousandth part of a second, and the average electric field change was about one-eighth part of a volt per metre. This is equal to 130,000 microvolts per metre.

Now 20 to 30 microvolts per metre is about the strength of a signal wave as received on a good valve receiver. Hence the atmospheric waves may have an amplitude more than several hundred times (perhaps 1,000) as great as most signal waves and can, therefore, drown them out completely. In the quasi-periodic type of "atmospheric" there is no unbalanced transfer of electricity to the earth, but seven out of eight of the aperiodic strays carry positive electricity *from* the earth or send negative electrons down to it. This, as Professor Wilson found, is the direction of transfer in most lightning flashes.

The general result of research seems to be that the chief source of these atmospherics are lightning discharges. Although in our climate thunderstorms are not frequent, yet Mr. C. E. P. Brooks has shown from statistics that about 2,000 thunderstorms may be in operation at a

given moment, taking the earth as a whole, and that this discharge of electricity represents the release of an enormous amount of electric power of about 1,000 million kilowatts. Hence, there is an ample supply for all the energy of the atmospherics. Also, strong evidence is available to show that lightning discharges, at a 1,000 to 2,000 kilometres distance, produce sensible disturbances on our modern receivers. Arguing from experiments by Mr. C. T. R. Wilson that a lightning flash conveys about 20 coulombs in electric quantity, Professor Appleton has pointed out that a lightning flash is a sort of transmitting aerial wire 2 or 3 kilometres long and traversed by a current of 10,000 amperes for about $\frac{1}{500}$ of a second.

Much research work has been done by Mr. Watson Watt and by Mr. Hoyt Taylor on Atmospherics, using direction-finding aerials, with the result that their direction is found to vary during the day. Also, that when tested with a loop aerial there is a very distinct maximum and minimum in certain directions.

It may be possible before long, by simultaneous observations at various places, to locate the exact source of an atmospheric, just as it is now possible to assign the locality of an earthquake by seismic records at various places.

Some of the schemes for eliminating atmospherics depend on this fact, but experience supports the results of research that it is impossible to cut out atmospherics when at all strong merely by resonance methods in the receiver, as the action of a powerful aperiodic wave on the aerial is to give it a shock which causes oscillation in the receiver of the natural period of the latter.

Meanwhile, however, in spite of much research, the problem of excluding atmospherics from our receivers is still very imperfectly solved.

It will, therefore, be evident that an enormous amount of pure scientific research by many of the most skilful investigators in the world has had to be undertaken to lay the foundation and erect the structure of modern wireless telephony in the form of broadcasting so familiar to us all.

Furthermore, the great achievement of practical transatlantic wireless telephony has at least had a beginning, even if not yet free from all difficulties.

This great feat is entirely due to the improvements made in the thermionic valve. First, by the invention of a metal bulb or external anode water-cooled valve by means of which large amounts of electric power can be transformed from the condition of direct-current to high-frequency electric oscillations, and these again transformed into carrier electric waves, radiated from an aerial the amplitude of which can be modulated by a microphone in accordance with the wave form of speech sounds.

In this manner several hundred kilowatts of power can now be thrown out into space in the form of modulated electromagnetic waves, and a single voice can address the whole known world. The power of receiving these electric waves and separating out the speech undulations from the carrier wave so as to affect a receding magneto telephone is entirely due to the amazing properties of the three-electrode thermionic valve in amplifying and rectifying high-frequency electric currents.

Enormous ingenuity has been brought to bear upon the construction of these valve receivers, which has initiated a new trade with a new technique and new literature of its own. We are rapidly approaching the time when the evolution of this appliance will convert the whole inhabitable earth into one vast auditorium, in which a single person can address listeners in any place who are provided with the necessary receiving apparatus.

The chief danger in front of us is that the ether or electromagnetic medium in which these waves travel is becoming agitated by such storms of conflicting waves that the enterprise of broadcasting may break down owing to its own success

The chief improvement now required, in addition to some method of excluding "atmospheric" or vagrant waves from our receivers, is some simple means of cutting out the intrusion of the exasperating Morse signals sent

from ships and shore stations. These spoil to a large extent the reception of broadcast music and speech for listeners at places anywhere near the coast-line of frequented sea highways, such as the English Channel, by the *rat-tat-tat* sounds which break in at repeated times and murder sometimes the finest music. Nothing would be a greater gain for the invaluable broadcasting than the invention of some means to get rid of this nuisance. It can probably only be done by the institution of fewer well-distributed broadcasting stations of high power, so as to enable listeners-in to use less sensitive receivers for long distance reception.

CHAPTER VI

SURGES AND PRESSURE RISES IN ELECTRIC TRANSMISSION LINES

The enlargement of the scale of our operations in electrical engineering often raises new and difficult problems for solution. Achievements which presented no particular obstacles when carried out on a small scale frequently bring us in contact with very serious difficulties when the scale is multiplied by 10 or 100. We then find that merely empirical rules are not a sufficient guide, but that careful systematic scientific research is essential to overcome them. This has been seen to be the case in a marked degree in connection with the problem of distributing electric power over large areas by means of alternating electric currents.

In the earliest days of electric lighting, when direct currents began to be used for arc and incandescent lighting, the electric knowledge required was of an elementary kind and did not extend beyond the general facts of the resistance of conductors and breakdown voltage of insulators.

As soon, however, as alternators and transformers began to be devised and constructed, and attempts were made to distribute by high voltage alternating currents, the importance of the quality called inductance became obvious.

It was not until Ferranti, with his bold conceptions, induced financial supporters to embark on the construction of the Deptford station, about 1890, and its long concentric paper-insulated mains laid from Deptford to London, that capacity effects, so familiar to us now, made their appearance in a marked and very ominous manner.

It is clear that a sufficiently analytical and highly trained scientific mind could have foreseen these effects from general principles, but as a matter of fact no one did foresee them, and what happened was that the scientific method had to be applied to unravel the reasons for the troubles when they occurred and to find a remedy for them.

For the first attempt at alternating current distribution on a large scale, Ferranti had designed tubular armoured concentric mains, formed of two copper tubes with impregnated paper insulation. As he intended to earth one pole of his alternator, he considered that the insulation between the outer copper tube and steel containing tube might be light compared with that of the insulation between the copper tubes. The latter had to sustain 10,000 volts pressure, but the former only the voltage drop down the mains.

These mains were each about seven miles long, and there were four of them made as follows·

One conductor consisted of a copper tube $\frac{9}{16}$ in. inside diameter and $\frac{13}{16}$ in. outside. This was overlaid with manilla paper, impregnated with a resinous compound, and over this was a second copper tube, $1\frac{27}{32}$ in. inside and $1\frac{15}{16}$ in. diameter outside. The outer tube was covered with a light insulation of the same manilla paper and then enclosed in a steel tube These tubes were made in 20-ft. lengths and then jointed together. These conductors had a capacity of about $\frac{1}{3}$ microfarad per mile.

It was originally intended to make the alternators generate at 10,000 volts and connect the high-tension mains at that end direct to the alternators.

In consequence of troubles connected with the flashing over of the current from the copper strip armature to the field magnets, certain of the alternators were altered to reduce their generating voltage to 2,500, and then this was stepped up to 10,000 by transformers at the sending end and again reduced to 2,500 by similar banks of transformers at the London end and then at distributing

stations to 100 volts for house supply. On setting this system into regular operation two effects were found which had not been anticipated. First, the insulation between the outer copper tube and the steel armour tube continually broke down, especially when concentric mains were switched on and off the bars at the generating station; and secondly, the adding or subtracting of mains from service altered the pressure at the London end even when the excitation of the alternators was kept constant.

These difficulties required careful analysis and experiment to ascertain their cause and cure. Without relating these investigations in historical order, suffice it to say that the first trouble, viz., the breakdown of outer insulation to earth was in large measure due to the use of air-break switches at the generating end, which did not enable a control to be exercised as to the phase of current at which the circuit was opened or the order in which the connection and disconnection of the inner and outer conductors was made to the bus bars. Each of the mains having a total electrical capacity over the seven miles or so of 2 microfarads, and the frequency being 83 and voltage 10,000, the capacity current of the mains when 1, 2, 3 or 4 were connected in parallel, was 8, 20, 31 and 44 amperes, as found by experiment when the circuits were open at the London end. These values agreed fairly well with the predicted values from the theoretical formula, $A = \frac{CV2\pi n}{10^6}$.

Hence, if the outer conductor was disconnected first at the sending end, then on breaking the inner connection a large current flowing in an inductive circuit was possibly interrupted, and this current had its only path back to the earth end of the alternator by flowing through the dielectric between the outer conductor and earth. The result was frequently the breakdown of that insulation.

The trouble was only finally cured by the invention of a

mains-charging gear, which controlled the order of operations in connecting and disconnecting the mains from the bus bars and, moreover, only allowed the capacity current of the mains to rise up or be reduced very gradually, and not start or stop it at full value. The order of operation was that the alternator connection was first made to the outer conductor and then to the inner through a gradually reduced impedance. In taking a main off the order was reversed and the current reduced, first gradually, and then the outer connection not broken until after the inner connection. In this manner breakdown of the outer-to-armour insulation was prevented. The second effect or rise of pressure on switching in mains was a complex effect and required special experiments to dissect it.

Briefly, it was as follows : Part of this rise of voltage was a resonance effect, due to the reaction of the capacity of the mains on the inductance in series, being chiefly that of the circuits of the transformers at both ends. This phenomenon of electrical resonance had already been the subject of theoretical treatment by Dr. J. Hopkinson, Mr. Blakesley and others, and, as far back as 1878 or 1879, Mr. Munro had shown that a condenser attached to the terminals of an alternator could produce an increase in the terminal potential difference (see note at end of this chapter).

In the case of the Ferranti arrangement above described, there appeared to be two other causes at work in raising the potential difference of the mains. One of these was, as proved by experiment, a change in the transformation ratio of the step-up transformers at the sending end, due to a diminution of the magnetic leakage drop, following on the advancement of the phase of the current by the capacity of the mains.

Another cause of a kindred nature was found to be the diminution of the armature reaction in virtue of which the armature current of an alternator tends to weaken the field magnets when it is worked on an inductive circuit,

but to strengthen them when it is connected to a circuit having sufficient capacity.

These various effects were traced out by a set of special large scale experiments made with the Ferranti mains in the early part of 1891, and described by the author in a Paper read to the Institution of Electrical Engineers, in May, 1891. They had the effect of clarifying the complex phenomena and providing a remedy in a rough manner by the control of the alternator excitation by rheostats at the moment of switching mains on or off the bus bars.

In modern alternating current stations the alternator voltage is regulated automatically by self-acting pressure regulators, which control the field current of the alternator, such as the Brown-Boveri or the Tirrell regulators. Before passing on to consider the troubles involved in working aerial lines, one other effect which presented itself in the early days of alternate current working may be mentioned, viz., those due to the switching in of transformers, which were a cause of failure. These were discussed for the first time in a Paper read by the author to the Institute of Electrical Engineers of London, in 1892, and the reasons for them given. When a static transformer is switched out of circuit, after having been in use, by an air-break switch, the core may be left magnetised in one direction or the other, according to the phase of the current when the circuit is finally opened. On closing it again the current begins to flow in such direction as to increase or diminish the residual magnetism of the core. If the former, then a counter electromotive force is produced, which prevents the current rising above a certain value. If the latter, then there will be a rush of current into the transformer, which will only be arrested when the cyclical magnetisation of the core has settled down after a few periods into proper phase relation to the current.

The sudden arrest of this current rush produces a rise in electric pressure which does damage.

The author showed by experiment, in 1892, by inserting

carbon filament lamps and other devices in the primary circuit of a transformer, that these current rushes do actually take place once in a while on switching on, and can only be prevented by the use of a suitable controlling step-by-step switch, and by the use of an oil switch to open the circuit.

We must in the next place discuss the dangerous effects which are capable of being produced in aerial high tension power supply lines by atmospheric electric discharges, and the manner in which research has provided the means of combating them.

When currents are flowing in a network of conductors there is at every point a certain current and a certain voltage in the system.

It was only after researches began to be made on electric waves, both in space and along wires, about 1885 to 1887, it was recognised that if in such a system a sudden change is made in current or voltage at any point, electric equilibrium is only established by the propagation of electromagnetic waves travelling along these wires. If the pressure or current changes by a large amount in a comparatively short distance along a wire, say a few yards, the wave is said to have a steep front. If the disturbance only involves the passage of a single rapid change of potential it is called a *surge*, and it may be a steep-fronted surge of potential or of current.

The things most dreaded by the practical station engineer are these steep-fronted potential surges, because if they travel into transformers or alternators they will produce immense differences of potential between adjacent turns or layers of insulated wire and puncture the insulation, thus causing damage often very expensive to repair.

Hence very considerable scientific study has been given to these surges and the appliance for rendering them harmless

These steep-fronted surges may arise (i.) either from atmospheric electric discharges, or (ii.) normal operations of switching in or out, or the action of protecting devices,

such as fuses or circuit breakers, or (iii.) from sudden failure of insulation. In temperate climates we are not much troubled with thunderstorms, but in tropical and mountainous countries they are very frequent.

In the upper regions of the atmosphere the strong ultra-violet light of the sun ionises the air and produces positive ions of atomic dimensions and negative ions and electrons.

The earth, as a whole, generally has a negative charge, the origin of which is still obscure, and it is surrounded by a strong self-produced electrostatic field. As soon as rain falls the sea or earth's surface becomes positively electrified.

The prevailing negative charge is, however, continually being dissipated.

In fine weather the electric force near the earth is at the rate of 100 to 150 volts per metre, but decreases as we rise upwards. Hence this force tends to draw positive ions down towards the earth, and the total downward current over the whole earth amounts to about 1,000 amperes.

The mobility of negative ions or electrons is far greater than that of positive ions, and the electrons are the chief means of transport of electricity. Clouds may therefore become charged either with electrons or positive atomic ions, and electric discharges may take place between the earth and electrified clouds, or between clouds, or from one part of a cloud to another. Positively charged clouds are much more common than negatively charged, as shown by Dr. G. C. Simpson.

Although sunlight can ionise air molecules, the principal agent in producing the atmospheric charges is, according to Dr. G. C. Simpson, the breaking of raindrops by upward currents of air. Dr. Simpson has shown that when drops of water fall through a current of air and are split up into smaller drops, these small drops are positively charged, whilst negative electricity passes into the surrounding air. He has shown that a raindrop cannot

be larger than ¼ in. in diameter and such a drop falls through air at a rate of 24 ft. a second. If then a current of air is moving upwards with greater velocity than 24 ft. per second and carrying up moisture to be condensed into waterdrops, the large drops, on breaking up into smaller ones, leave these latter positively charged, whilst the air current passes on upwards and carries with it the negative charge. Hence we obtain positively charged clouds and negative electricity in the higher regions of the atmosphere.

These positively charged clouds may, when their potential reaches a certain limit, discharge to the negatively charged earth in the form of a lightning flash.

The positively charged cloud produces an induced negative charge on all conductors beneath it, such as aerial lines connected to earth. Air at ordinary pressures can withstand an electric force of about 30,000 volts per centimetre, but when it exceeds this the air molecules are ionised and it passes suddenly into a conducting condition. The electrically-charged cloud produces an intense electric field between it and the earth, and when that exceeds a critical value a discharge in the form of lightning takes place. At that moment, the "bound" negative charge on the aerial wire is released, even though the lightning flash may take place at some distance. The potential of the line then changes very suddenly and may jump up thousands of volts. We are here concerned in these atmospheric electrical phenomena with enormous potentials and energies. From statistics, Mr. C. E. P. Brooks has concluded that about 1,800 thunderstorms on an average are in operation at any instant all over the earth, producing in all about 100 lightning flashes per second. The average electric quantity in a flash is of the order of 20 coulombs, and the potential difference at the ends of a flash of the order of 10^9 volts. Hence the power expended in producing the flashes in action at any instant is of the order of 10^9 kw. or 1,300 million horse-power.

Taking the earth as a whole, a current of about 1,000

amperes is flowing from the clouds to the earth (see the note at end of this chapter).

When, then, a " bound " negative charge on an aerial line is set free by an adjacent lightning flash the consequences will depend upon whether the potential of this charge added to that of the line causes a flash over and

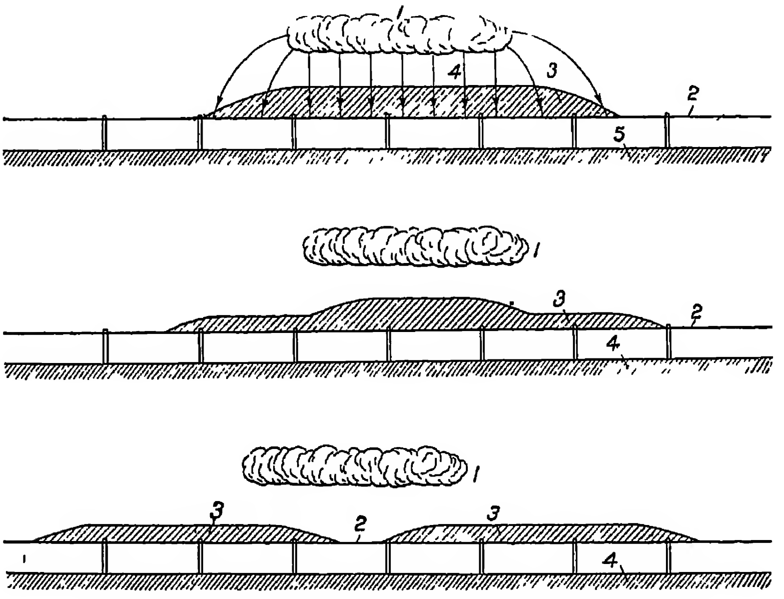


FIG. 47.—This diagram represents an aerial power line (2), over which is a positively charged thunder cloud (1). This induces a negative " bound " charge (3) on the line The shaded part represents this induced charge If the cloud discharges without producing a flash-over on the line at an insulator, then the negative bound charge becomes free and leaks away to earth.

arcing at a line insulator, thus putting the line momentarily to earth. If the flash over does not take place the " bound " charge simply flies away and leaks to earth at various places without damage (see Fig. 47). If, however, an arc-over does occur, then the potential of the line at that point drops to zero and a large current to earth takes place. This at once generates a steep-fronted surge,

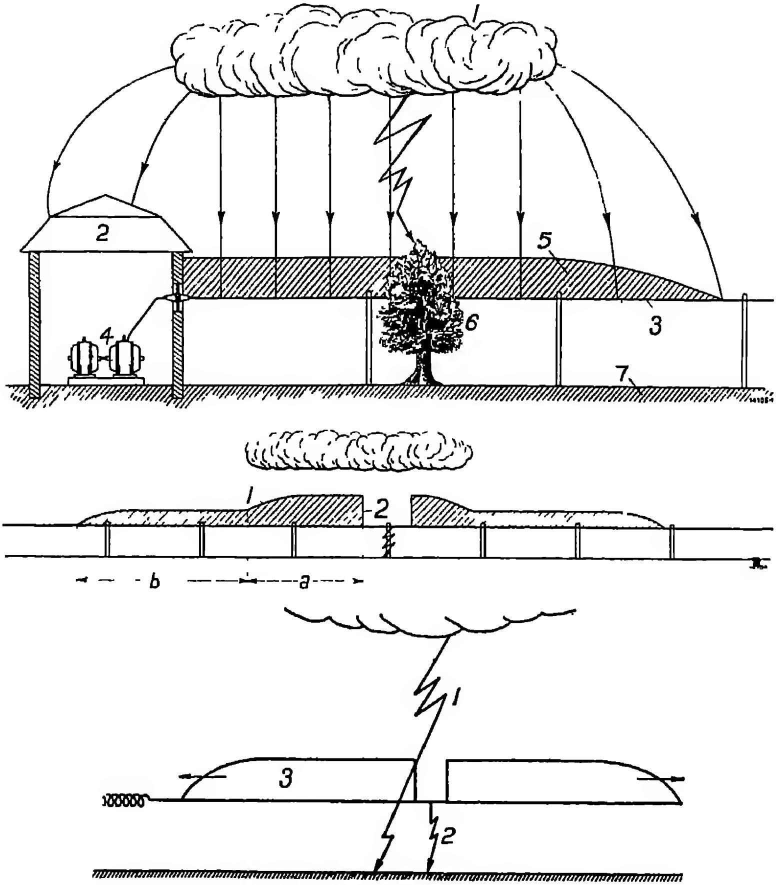


FIG. 48.—If when the cloud (1) discharges and the bound charge on the line becomes free, this potential added to that of the working voltage of the line produces a flash-over at a line insulator, then the line may be put to earth at that point and a steep-fronted surge produced which flies outwards.

which travels away from that point with the velocity of light, and its damaging properties depend on the steepness of the front (see Fig. 48).

The amplitude of these surge potentials may be very large. At Upsala, some data have been obtained of late

years by Norinder with an artificial line built for the purpose. When a thundercloud is over a short aerial line atmospheric electric fields or potential gradients have been observed of as much as 140 kilovolts per metre. When lightning discharges take place the sudden rise in potential at some point in the line may easily amount to 30,000 to 50,000 volts, as observed on the Wengernalp railway.

As the breakdown pressure of insulators on lines worked at 50 kilovolts is about 100 kilovolts, it follows that in plants whose working pressure is less than 100 kilovolts surges may arise where potentials exceed the electric strength of the insulators employed.

In addition to the surges produced by the release of induced charges on the line due to atmospheric electricity, similar steep-fronted surges may be generated either by switching on or off long-feeder circuits or transformers, or by arcing grounds, that is, sudden failures of insulation and arcs which are blown out suddenly taking place between line and earth or between different phases.

Since these surges may create most expensive damage to plant very great attention has been paid to the design of apparatus for rendering them harmless.

Invention has taken several different directions. We may (i.) deflect the surge into a bye-pass circuit to earth but restrain the line current from following it.

This method includes the well-known (*a*) horn gap-arrester, (*b*) the aluminium electrolytic cells in series, and (*c*) the oxide film arrester (see Fig. 49). To limit the arcing current which follows the surge to earth, either water or metallic resistances have to be placed in series. There are many engineers who consider that the surge-protecting power of the horn gap-arrester is much over-rated, and that the sudden interruption of the arc starts a fresh surge in place of the original one it was intended to destroy. Also, water resistances are uncertain and metallic resistances expensive, whilst the horn arrester must be placed at frequent intervals along the line to be effective. The

aluminium cells and oxide film arresters require continual attention and will not function indefinitely.

Then, in the next place we may (ii.) endeavour to render the surge harmless by sloping off its steep front or by absorbing its energy and dissipating it harmlessly. The front can be sloped off by the use of (*a*) condensers connected between line and earth.

In this case the surge, when it comes along, darts into the condenser. The charge is then given out again on to the line, but being limited in rate of flow by resistance it is given out gradually and its sting is, so to speak, drawn. It then leaks away by various channels, but the line current cannot follow. The trouble has always been to find a dielectric for a condenser which would stand the voltage and yet be not too bulky and costly.

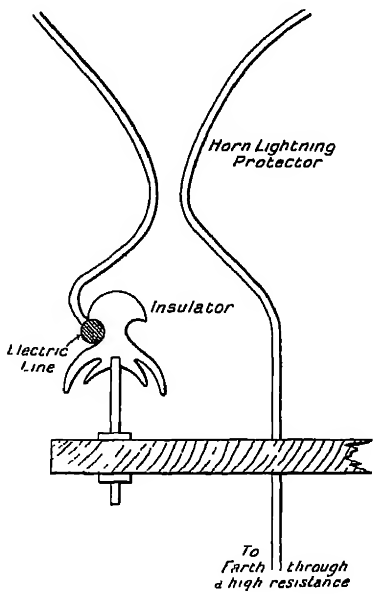


FIG. 49.—The Horn-gap lightning arrester

Glass condensers were devised by Moscicki, but are bulky and fragile. More recently a suitable dielectric has been found in the material called acetyl cellulose, mentioned in Chapter I., of which the trade name is "Cellon."

It can be prepared in thin sheets, has a fairly high dielectric constant (about 4·5) and dielectric strength, is non-hygroscopic and free from air pockets.

A long strip is silvered on both sides with perfect adhesion, and such strip is then rolled up so as to form a compact condenser, and unit sizes can be combined and

built up in a porcelain tube. In this form it is made in Great Britain by Messrs. Isenthal, of London (see Figs. 50 and 51).

Condensers, when of suitable capacity, say, 0·01 to 0·05 microfarads, can protect transformers against surges

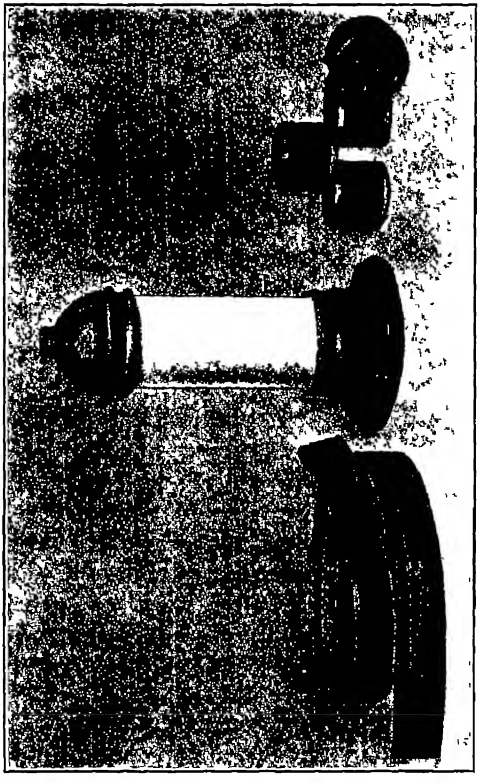


FIG. 50.—Structure of "Cellon" condensers made by Messrs Isenthal & Co., Ltd., for the surge protection of electric transmission lines

started by atmospheric electricity, but they are not a universal means of protection against abnormal pressure rises such as those produced on healthy phases of a three-phase system by sudden arcing grounds on one phase. Moreover, the selection of a suitable capacity is more or less empirical at present, and much scientific research is yet necessary to elucidate the questions at issue.

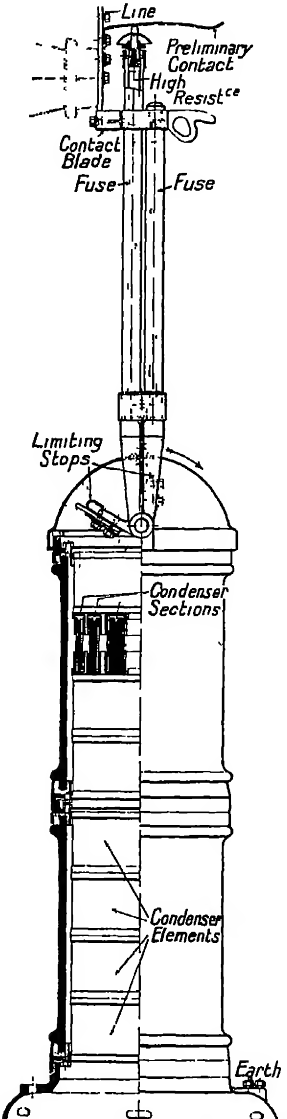


FIG 51 —Pillar containing condenser units, fuses, and switches for surge protection of transmission lines as made by Messrs. Isenthal & Co, Ltd., London.

It remains then to be considered the class of devices intended to absorb the energy of travelling surges without introducing into the line objectionable impedances in the form of choking coils, which are themselves liable to be broken down, and merely reflect the surge back.

The Ferranti-Grant surge absorber is virtually a transformer having a closed secondary circuit, consisting of a non-magnetic cast iron cylinder, which encloses the low resistance primary circuit. The primary circuit is inserted in the line. The impedance for the normal working frequency, say 50 cycles, can be arranged to be small, so that the power taken up in the arrester is not more, say, than 150 watts. If, however, a surge enters the primary, the surge energy is given up to the non-magnetic secondary circuit and rapidly dissipated (see Fig. 52). The great cooling power of the iron jacket enables it in this way to take up harmlessly large amounts of power.

One advantage claimed for it is that it does not earth the line.

We may then notice that if a surge does penetrate into a

transformer the damage done will nearly always be in the insulation of the end coils as the result of the great potential difference between proximate turns of wire. Accordingly, many transformer builders have paid special attention to thickening up the insulation of the terminal

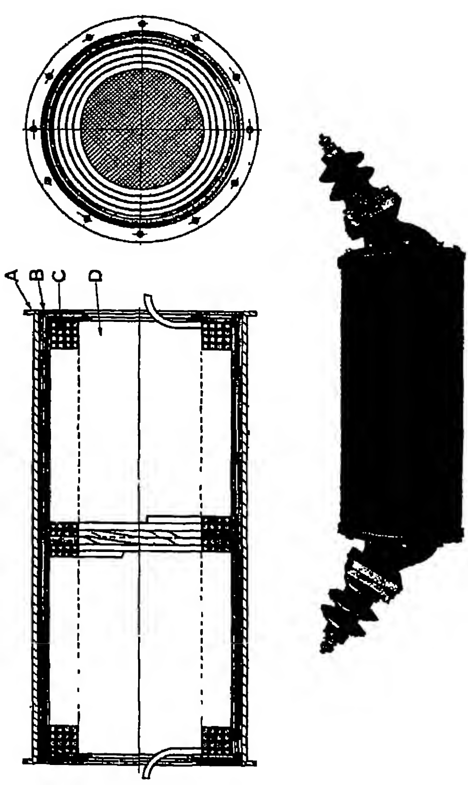


FIG 52.—Ferranti-Grant surge absorber. It consists of a primary coil of low resistance and a closed secondary circuit consisting of a cylinder of *non-mag* cast iron.

coils, and have maintained that this precaution is preferable to the use of protective devices. Both precautions are, however, necessary if protection is to be complete.

Apart altogether from the production of travelling surges and the effects of their steep fronts, there are super-pressures produced by electric arcs started between the lines and the earth. If such an arc-to-earth occurs on

one phase of an insulated line the voltages of the other healthy phases are at once raised, it may be to double normal value. Hence, flash over to insulators may occur and an arc to ground on another phase, in which case the line is dead short-circuited.

This is prevented in three-phase systems by earthing the neutral point. Whether it is most advisable to earth it directly or through an inductionless resistance or through an impedance or reactive coil is a question of importance.

By earthing the neutral point through a coil having inductance of a certain value it produces in the arc current to earth, when considered alone, a certain lag behind the line voltage, but as the line has capacity with respect to the earth these two factors may be made to more or less neutralise each other, and the arc is then more easily extinguished. Such coils are called extinction coils and have been used with advantage. Since the large generators now used have very small internal resistance and reactance and have immense current-producing power on short-circuit, it is very usual to limit this current by placing large current limiting reactances in the outgoing lines from the station, which are massive non-iron cored coils built into brickwork or cement, and sometimes their external magnetic fields shielded off by iron enclosing shields.

It must not be forgotten that large distribution systems of supply, having distributed capacity and inductance, can have powerful electric oscillations set up in them by spark or arc discharges to earth or phase to phase.

A long overhead power line is a sort of horizontal wireless aerial, and any arc at one end by switching on or off transformers will start electric oscillations which run along the line with the velocity of light. These are reflected at the far end and at points where the reactance or capacity of the line suddenly changes, and the oscillations, therefore, travel to and fro over a certain path. If this distance happens to be an integer multiple of a quarter wave length of the oscillation, resonance may

cause enormous multiplication of potential at the ends, and flash-over to ground may occur or breakdown of insulation with the accompanying production of steep-fronted surges or arcs to earth. It is difficult or even impossible to predict in the lay-out of the line if these resonance effects will occur or not.

The only protection against them is the use of one or other of the surge-protecting devices above described.

In the lay-out of large extra high pressure systems of supply the provision to be made for the prevention and speedy isolation of faulty line sections, transformers or generators, is of the greatest importance, and has been the subject of the most careful thought and experiment. In fact, it has become a special branch of electrical engineering work. The results of scientific research in many different directions have been laid under contribution to provide the necessary appliances. Since extra high tension (E.H.T.) supply is essentially used over large distances and requires long feeders or mains, one of the first requisites was the means of cutting out a faulty supply line which, if laid in duplicate along a separate path, will leave the service uninterrupted. One of the first of these methods was the Merz-Price balanced voltage system of feeder protection, which depends on the fact that in a line without fault the current leaving the line at one end is equal to that entering it at the other. A fault to earth upsets this balance, and the difference current can be caused to actuate relays which open oil switches at both ends of the line simultaneously.

The main centre of development of these fault-protecting devices has been the Newcastle Electric Supply Company, and their engineers have established a world-wide reputation in this matter.

In three-phase working, six transformers are required for the Merz-Price system, and three pairs of relays which are interconnected by a pilot wire three-phase system. Thus the relays are traversed by the capacity current of the pilot-cable, and any induced current due to out-of-

balance feeder current is superimposed on this. Accordingly, this fact limits the sensitiveness of the method.

An improvement on this is the Beard system with the sheath of the pilot cable split in the centre and using the Fawsett-Parry relay. In this method the capacity current of the pilot cable is not sent through the relay but is bye-passed. Accordingly, the relays can be set for greater sensitiveness without fear of accidental tripping. A further modification is the Merz-Hunter split conductor system. In this, each phase of the feeder is laid double, and the essential principle of the method is, that if a fault to earth occurs the equality of the currents in the splits will be upset, and this can be caused to actuate relays which trip oil switches at both ends.

It will not be necessary, nor will space permit us to describe in detail all the protective gear which has been devised for feeders, generators and transformers, especially as it is described in well-known text-books.

In the design of all parts, extensive large scale research has been necessary. As an instance of this the investigations made in Switzerland in 1915, and later in America and Germany, on the construction of oil switches, may be mentioned. The scientific investigations in connection with these were directed to the study of (*a*) the speed of separation of contacts, (*b*) explosion of oil and bursting of tanks, (*c*) fusing of switch contacts.

The conclusion of the Swiss Electro-technical Commission that it is unnecessary to increase speed of separation of contacts beyond 55 cm. per second does not seem to hold good for very large powers. The Americans found that in case of very large currents switch contacts were sometimes forced apart before the protective relays had operated, and sometimes fused together and held closed after the relays had operated.

It will be seen then that the results of scientific research in many different departments have made contributions to the explanation and elimination of very serious causes of disaster in high-tension electric power distribution.

Of these, the most serious are the atmospheric electric discharges in thunderstorms, and hence the elucidation of the mechanism of thunderstorms, though in one sense a purely scientific problem, has a vast influence upon the invention of devices for securing the safety of electric transmission lines from damage. The whole plant in generating stations has been destroyed in a few minutes, in some cases by the entrance into them of surges, from the attack of which high power transformers and alternators have not been sufficiently protected. The improvement and testing of these protective devices has therefore called for the most highly scientific ability.

A Note on the Capacity, Charge and Leakage Current of the Earth

The radius of the earth is roughly 4,000 miles or $r = 64 \times 10^7$ cm. and $r^2 = 41 \times 10^{16}$ (cm.)^2.

If the earth were a sphere in space its capacity in electrostatic units (E.S.U.) would be 64×10^7 cm. or $\dfrac{64 \times 10^7}{9 \times 10^5} = 711$ microfarads.

It is admitted that there must be a highly conducting layer of air at a height which is approximately $h = 100$ kilometres $= 10^7$ cm. Hence the capacity is that of a spherical condenser with radii r and $r + h$,

$$\text{or } C = \frac{r(r+h)}{h} = r + \frac{r^2}{h} = 64 \times 10^7 + \frac{41 \times 10^{16}}{10^7} \text{ cms.}$$

$$\text{or } C = \frac{41 \times 10^{16}}{9 \times 10^5} + \frac{64 \times 10^7}{9 \times 10^5} = 45{,}500 + 711 = 46{,}211$$

microfarad, or the capacity is 0·046 farad.

The fine weather potential gradient is about 150 volts. per metre or $E = 150 \times 10^6$ electromagnetic units. Hence, if this continues up to the conducting layer the voltage to which this terrestrial condenser is charged would be $150 \times 10^5 = 15 \times 10^6$ volts, or 15 million volts $= V$.

The earth's charge, which is *negative*, is then

$CV = 0{\cdot}046 \times 15 \times 10^6$ coulombs $= 700{,}000$ coulombs nearly.

There is, however, a leakage current of 1,000 amperes or 1,000 coulombs per second from the whole earth.

If then there were no means by which this negative charge could be replenished the charge would only last about 12 minutes. The earth's negative charge induces a positive charge on the lower levels of the conducting layer and repels negative electrons to a higher level. The earth, therefore, has a strong electric field round it, the normal direction being *towards* the earth and equal to 150×10^6 microvolts per metre or 15×10^7 E.M.U., or $0{\cdot}005$ electrostatic units $= \frac{1}{200}$ E.S.U. in fine weather, but greatly increased in storms.

As explained above, the majority of the raindrops which fall bring down *positive* charge to earth, which is in the same direction as the fine weather gradient.

In 1908, Dr. G. C. Simpson measured at Simla (India) the rain charge. For 76·3 c.c. of rain per square centimetre the charge was $+ 22{\cdot}3$ E.S U. and $- 7{\cdot}6$ E.S.U. or $+ 14{\cdot}7$ E.S.U., which for a whole year would equal a current of $1{\cdot}5 \times 10^{-16}$ ampere per square centimetre of earth's surface.

Professor Wilson concludes from certain experimental results that an ordinary thundercloud has opposite charges on its upper and lower surface.

In 61 per cent. of cases observed he found that the *upper* surface is *positively* charged and *lower* surface negative.

Hence the cloud would induce a positive charge on the earth beneath it and when a lightning stroke took place between the cloud and earth it would remove positive electricity from the earth or *bring down* negative charge, which would replenish the loss of normal negative charge.

The average quantity brought down per flash is about 20 coulombs.

The field strength or potential gradient just before

discharge may mount up to 1,000 volts metre, or even 100,000 volts metre.

A Note on the Rise in Voltage at the Terminals of an Alternator connected to a Condenser

Let E be the electromotive force of the alternator and V the potential difference of its terminals, and let L and R be the internal inductance and resistance of the alternator armature and C the capacity of the condenser. If then $p = 2\pi n$ where n is the frequency, and using ordinary vector notation in which $j = \sqrt{-1}$ and assuming a sine curve variation of E, we have the vector equations :—

$$\left(\mathrm{R} + \gamma p\mathrm{L} - \frac{1}{\gamma p\mathrm{C}}\right) \mathrm{I} = \mathrm{E}$$

$$\frac{\mathrm{I}}{\gamma p\mathrm{C}} = \mathrm{V},$$

where I is the current.

If we scalarise these equations and eliminate I we obtain the equation :—

$$\frac{\mathrm{V}^2}{\mathrm{E}^2} = \frac{1}{\mathrm{C}^2\mathrm{R}^2p^2 + \mathrm{C}^2\mathrm{L}^2p^4 + \mathrm{I} - 2\mathrm{LC}p^2}$$

In order that V may be greater than E it is sufficient that the product $\mathrm{L}p\,\frac{1}{\mathrm{C}p}$ shall be greater than $\frac{1}{2}(\mathrm{R}^2+p^2\mathrm{L}^2)$.

The quantity $\mathrm{L}p$ is called the reactance of the armature and the quantity, $\sqrt{\mathrm{R}^2 + p^2\mathrm{L}^2}$ is called its impedance and $\frac{1}{\mathrm{C}p}$ is called the capacitance of the condenser.

Hence the rule is that twice the product of the reactance and capacitance must be greater than the square of the impedance. Then, if so, the potential difference of the terminals of the alternator with condenser connected across them will be greater than the potential difference when the condenser is removed and the alternator with the same field excitation is running on open circuit.

CHAPTER VII

ELECTROCHEMISTRY AND ELECTROMETALLURGY

THE close interconnections of scientific research and electrotechnical applications are so evident in the case of electrochemistry and electrometallurgy that no treatment of the subject of this book would be otherwise than imperfect which omitted to make mention of some of them.

Even before the invention of the voltaic pile by Volta, it had been ascertained that the electric spark from a frictional electrical machine could effect chemical decomposition. Beccaria had found that by this means metallic zinc or mercury could be obtained from their oxides, and Joseph Priestley had discovered that from water a gas could be evolved, subsequently called hydrogen. Volta, in 1799, gave us the means of producing much larger electric currents of lower voltage, and one year later, Nicholson and Carlisle had decomposed slightly acidulated water by the voltaic pile and liberated freely two gases from it.

A year after that date, Davy, in the laboratories of the Royal Institution began his great researches and produced metallic Potassium and Sodium from their fused hydrates by the current of his large voltaic battery, whilst in 1808, Calcium, Barium, Strontium, and Magnesium, were obtained as metals by electrolysis of their compounds. Berzelius then propounded his electrical theory of chemical combination, regarding chemical union as the result of electrical attractions between oppositely electrified atoms.

It was soon recognised that whilst some solutions or liquids are easily decomposed by the current, others are not; but the reason for this distinction was for long obscure.

In 1834 Faraday began that series of scientific researches which threw a flood of light on the whole subject. These are described in the Fifth, Seventh and Eighth Series of his *Experimental Researches*. The terminology or words which he used were coined for him by Dr. Whewell, the famous Master of Trinity College, Cambridge.

Liquids which can be decomposed were called *electrolytes*, the metallic or other poles by which the current is led in and out were named the *electrodes*, *anode* positive, and *cathode* negative, and the products of decomposition were called the *anion* and *cathion* and the two, the *ions*.

Faraday established, by rigorous experiment, two fundamental laws: (i.) that the mass of either ion deposited on the electrodes is exactly proportional to the quantity of electricity which has passed, and (ii.) that when the same electric quantity passes in succession through two electrolytes the masses of ions liberated are in the ratio of their chemical equivalents. The number, therefore, which gives us the amount of electricity in coulombs necessary to deposit a gram-equivalent of any monovalent ion, say, 107·66 gm. of silver, is a very fundamental constant. It is equal to 96,500 coulombs.

A question of importance then is · What constitutes an electrolyte? Why is it that metallic salts are easily resolved by the current into two ions, but substances, such as aqueous solution of sugar or pure water or alcohols, are not resolved?

It is not necessary to deal at any length with the various answers to this question. Suffice it to say that Dr. Svante Arrhenius, in 1887, gave an answer which has now been generally accepted, though much opposed at first.

Briefly, it is that when a metallic salt, such as sodic chloride, is put into water it is to a large extent ionised, that is to say, separated into a free metallic ion and an acid ion, which are oppositely electrified. The reason for this is found in the high dielectric constant (80) of

water. In the normal or solid condition these salt ions are held together by electric attraction.

But the force between two oppositely charged bodies is inversely as the dielectric constant of the surrounding medium. Hence, when put into water the force is reduced and the ions fall apart. The objection that was urged against this view was that sodium and potassium and other such electropositive metals cannot exist in the free state in water. Metallic sodium, for instance, decomposes water and forms sodic hydrate in accordance with the chemical equation :—

$$Na + OH_2 = H_2 + NaHO.$$

This objection is, however, invalid because it ignores the great difference between a neutral and an ionised atom. The neutral atom of sodium has 11 planetary electrons revolving round a nucleus charged with 11 units of positive electricity ($+ 11e$). One of these planetary electrons lies farther out than the others and is easily detached. It is called the valency electron. If it is detached the remainder of the atom is called a sodium ion, and it has a positive charge of 1 unit ($+ 1e$).

The atom of calcium has two valency electrons, and if these are removed the calcium ion then possesses an electric charge of 2 positive units ($+ 2e$).

As already mentioned in Chapter I, the planetary electrons are arranged in certain rings, called the K, L, M, etc. rings, and the innermost ring seems always to contain 2 electrons. There seems also to be a great desire on the part of the atom to make up successive rings to 8 or 18 electrons, and the reason is probably a greater stability. The atom, apparently, can reach this greater stability by giving up, or taking up, electrons. Thus, the Na atom, when electrically neutral, has 11 electrons It tends to give up 1 because then it settles down into the $2 + 8$ conditions. It is then a sodium ion, and *ions*, though electrically charged, seem more stable than neutral atoms.

The oxygen atom in its neutral state has $8 = 2 + 6$

planetary electrons. It, therefore, desires to *take up* two more on its outer ring to get into the 2 + 8 condition, and then it has a $2e$ negative charge. This taking up of the supplementary electrons may be done by *sharing* electrons with another atom.

Thus an oxygen atom can acquire the two extra desired planetary electrons by uniting to itself 2 atoms of hydrogen. Each of the latter consist of a single proton or positive unit of electricity united to a single electron or negative unit. The two electrons of these atoms are then shared with the oxygen atom, thus producing a molecule of water.

If, however, one or both protons of the hydrogen atom have the chance of taking up a free electron, they will re-form a free atom of hydrogen in preference to sharing an electron with an atom of oxygen. If, then, one of the hydrogen protons is removed in this way from a molecule of water by the free electron coming from an atom of sodium, then the residue of the water molecule, now called hydroxyl, comprises an atom of oxygen and one of hydrogen, which together have one unit of negative charge. This can then combine with the sodium ion, which has one unit of positive charge to form a molecule of sodium hydrate. But a sodium ion cannot give up another negative electron. Hence it can exist in water as an ion. Accordingly, when we form a dilute aqueous solution of a metallic salt, most of that salt exists as free (+) metallic and (—) acid ions in the water. If we put 1 gram. of sodic chloride (Na Cl) in 100 c c. of water then 81 per cent. of the sodic chloride exists as free ions (+ Na) and (— Cl).

If, then, we insert two electrodes of materials not acted on by water, and bring them to different potentials, the two ions march in opposite directions with different speeds. At 18° C. the sodium ion (+Na) moves 43·5 cm./sec. and the chlorine ion (—Cl) 65·5 cm./sec., each carrying one electron charge $=4{\cdot}775 \times 10^{-10}$ E.S.U. This speed increases very rapidly with rise of temperature.

Those substances, like sugar, which are not resolvable into two ions are not electrolytes.

It is not, however, essential to have a solvent. Fused, pure substances, like sodic hydrate (NaHO) can be electrolysed in the liquid condition. X-ray analysis has shown that in a solid the atoms are arranged in a regular lattice. In sodic chloride it is a cubic lattice with sodium and chlorine ions at alternate points. Hence a particular atom of sodium (Na) is not joined permanently to, nor belongs to, a particular atom of chlorine (Cl). When such a salt is fused the rapid atomic motion brings together into temporary union atoms of, say, Na and Cl, and then separates particular pairs of ions so that the dancing couples are, so to speak, constantly changing partners, and do not dance in persistent pairs. Hence, at any temperature there is a certain proportion of them free and in combination, and if an E.M.F. acts on the fused salt the ions migrate in opposite directions during the time they are *free*.

When the metallic ion reaches the cathode it takes up one or more electrons and returns to the atomic condition. This metallic atom is either deposited on the electrode or acts upon the solvent by a secondary action.

Faraday's first law, therefore, provides us with a means of exactly measuring electric quantity, as for instance, by the electrolysis of a neutral solution of silver nitrate, in which case 1 coulomb causes a deposit of 0·001118 gm. of silver on the negative electrode. In the early days of electric lighting Edison employed the electrolysis of zinc sulphate with zinc electrodes to measure the electric quantity and energy given to a house.

An almost immediate outcome of the study of the laws of electrolysis was the foundation of three great industries, viz., electroplating, galvanoplastic copying and the preparation of pure metals by electrolysis.

The oldest of these is that of gold and silver plating, in which a thin layer of adherent gold or silver is deposited

from a double cyanide of gold or silver and potassium on an object of inferior metal. To keep the bath constant the anode must be a plate of gold or silver, and the current density has to be exactly adjusted to secure an adherent reguline deposit which can be polished.

The large industry of nickel plating has grown up since employing as a bath nickel sulphate in a dilute citric acid solution and a nickel anode. The object to be plated has first to be carefully cleaned. In galvanoplastic work the metallic coating is required to be non-adherent, and if it is of non-conducting material it has to be given a surface conductivity by a thin coating of graphite.

In this manner the original or master wax records taken for gramophones are electrolytically coated with copper. Then this negative is backed with a block of type metal and used to reproduce, in some material capable of being made soft by heat, the actual records which are sold. A very similar method is employed in the production of printing blocks for book or paper illustrations from photographs taken with the gelatine and bichromate process.

The production of pure electrolytic copper is one of the basic industries on which electrical engineering depends, and has assumed enormous dimensions, nearly a million tons per year. In the early days of submarine telegraphy it was found that minute non-metallic impurities in copper had an immense influence on its electric conductivity. Mathiessen's scientific work on this matter was of great importance.

If, however, a solution of copper sulphate, made from impure copper, is electrolysed we get pure copper at the cathode and the impurities are left behind near the anode as anode sludge, and this may contain percentages of gold, silver or bismuth which are worth extracting.

Here again the technical applications repay their debt to pure science by providing us with high conductivity, Cu wire having nearly 2 per cent. more conductivity than Mathiessen's standard.

Another electrolytic process of vast commercial importance is the production of metallic aluminium. Aluminium is one of the most widely diffused elements in nature, but its affinity for oxygen is so great that up to 1886 or 1887 metallic aluminium was almost a chemical rarity.

In or about 1886 or 1887 two young chemists, C. M. Hall, in America, and P. T. L. Héroult, in France, discovered that aluminic trioxide (Al_2O_3) dissolves easily in a fused mixture of cryolite (Al_2F_62NaF) and fluorspar (CaF_2).

The Al_2O_3 used is prepared from Bauxite, a crude aluminic hydrate, and the three materials in a state of powder are fused in an iron pot lined with graphite, a graphite anode leads in the current and the metallic Al accumulates at bottom of pot and is tapped off. Each pot requires an electromotive force of 6 volts, and a current of 7,000 to 10,000 amperes is used; or about 65 horse-power. With this voltage only the Al_2O_3 is electrolysed. The process is carried out on a large scale at Niagara, at Neuhausen, in Switzerland, and on Loch Ness, in Scotland. The yield is about 1 lb. of aluminium per 12 electrical horse-power hours.

Research has also revealed very valuable alloys of aluminium with other metals. Thus *magnalium* is aluminium alloyed with 3·15 per cent. of magnesium, and in spite of the affinity of magnesium for oxygen the alloy is less easily oxidised and is harder and has a less density than pure aluminium. The Germans used an aluminium alloy for framework of their zeppelins.

As is well known, a considerable amount of success has attended research intended to give us the closely related metal *beryllium* as a commercial product. The electrolytic production of this metal has advanced to rather beyond the experimental stage, but it is too soon yet to say if it can replace aluminium. The atomic weight of Be is 9 and its density is 1·8 against 2·7 for Al. But Be appears to be much more brittle than Al and not so easy to draw into wires or press to shape. Moreover, the salts

from which it is electrolysed have a much higher melting point, viz., about 1,200° C. as against 875 to 950° C. for the fused cryolite and fluorspar. Beryllium resists corrosion by alkalies and has greater tensile strength than aluminium. There is, however, a wide field open for research into alloys and electrical qualities.

Although the principal source of aluminium has so far been bauxite, yet research has been busy in trying to find means to extract it from other sources, particularly aluminic silicates, which form the basis of clays and widely extended earth crust materials.

A method was developed by Buchner, in Germany, during the war, of preparing it from kaolin or clays rich in kaolin, that is, porcelain clay. Victor Goldschmidt, in Christiania, has devised a process of getting it from labradorite. It is of great importance that research should find a cheaper material than bauxite and a process of preparing metallic aluminium from common clay.

We also require to find aluminium alloys of greater tensile strength so that reinforced concrete could be made with such alloys as a skeleton.

The amount of accessible iron ore of good quality in the world is not by any means unlimited, and unless we are more careful and economical in its use there lies ahead of our so-called civilisation a period of coal and iron starvation, which will put an end to progress as we now understand the word.

We may next refer to the relation of research to those processes in which the electric current acts simply as a heating agent and which, therefore, can be effected with a single, two- or three-phase alternating current.

The laws of electric current heating were first established by J. P. Joule, in 1841. He was a Manchester brewer by profession, but an accomplished amateur experimentalist in his leisure time In 1841, he published a memoir *On the Heat evolved in Metal Conductors of Electricity*, in which he proved experimentally the so-called Joule's law, that the heat produced by a current

in a certain conductor is proportional to the square of the current strength.

There are three ways in which we may obtain this electrical heating : (i.) We may pass a current through the object itself to be heated, this current being generated either by an external E.M.F. or by an induced current in the object itself ; (ii.) we may heat by a current a special resistance material and, by contact with it or radiation from it, heat the object to be heat-treated ; or (iii) we can produce an electric arc, using either two separate graphite

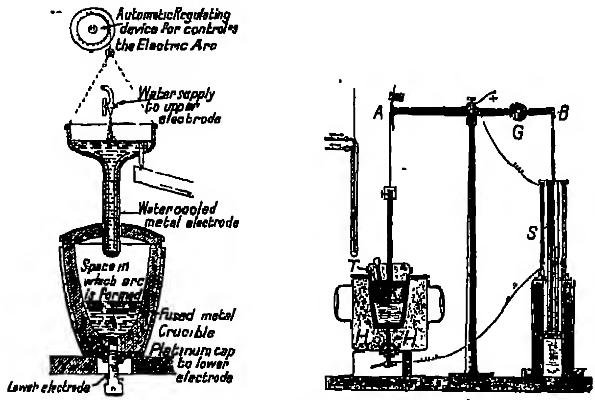


FIG. 53.—Early experimental electric furnaces with which Sir William Semens first melted steel electrically.

arc electrodes or making use of the thing to be heated as one of the electrodes.

This arc heating is the oldest of the three methods, and was first employed in scientific researches, bearing on electrotechnics by Sir William Siemens, in 1879, and by Henri Moissan, in France, in 1892–93, and one of the results of the work of the latter was the re-discovery of a method of producing calcium carbide. Siemens endeavoured to find if it could be profitably used for iron smelting. He placed some scrap iron in a plumbago-lined iron crucible and brought down an iron water-cooled electrode on it so as to pass the current from a dynamo through the metal (see Fig. 53) He found that with the

electric energy as supplied from a steam-driven dynamo 1 lb. of steel was melted in his furnace by the expenditure of 1 lb. of coal under the boiler of the steam engine driving the dynamo. This showed that the process was not, therefore, commercially impossible. The use of graphite electrodes was a drawback because of the possible contamination of the metal with carbon. Hence, in 1898, Major E. Stassano, in Italy, employed a furnace, comprising an iron cylinder lined with magnesite or refractory material, and melted steel in its crucible base by radiation from a three-phase arc (see Fig. 54)

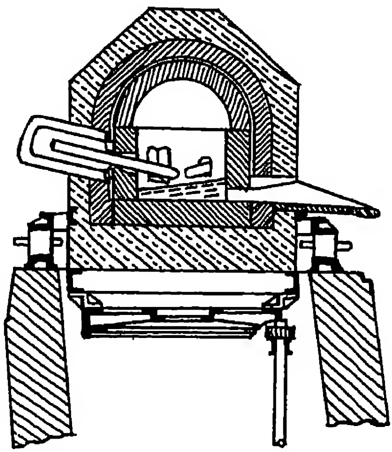


FIG 54.—Stassano's arc electric furnace employing a three-phase electric arc.

Paul Héroult made, in 1879, a modern form of arc furnace, in which two immense graphite electrodes pass through openings in the lid of a fireclay-lined iron furnace, into which a charge of scrap iron, lime and oxide of iron is placed. The arc springs from carbon to carbon or else to the charge, and when the scrap has been melted and has by oxidation or reduction reached the required composition it is drawn off at the bottom or else the furnace tilted and the charge run off at a spout (see Figs 55 and 56).

Such furnaces were in large use during the war and since to re-melt scrap iron and steel borings and turnings into cast-steel bars.

Moissan's early work with the arc furnace, used as an implement for scientific research, furnished much information as to the mode of using such a furnace in large scale metallurgical operations. The trouble with the arc

furnace is the contamination of the molten charge with carbon from the graphite electrodes. This is avoided in

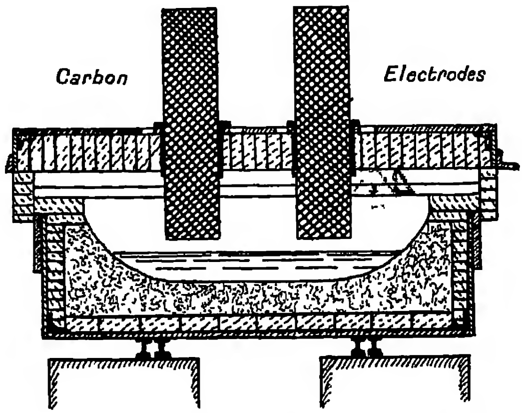


FIG. 55.—Héroult's arc electric furnace with two graphite electrodes passing through the lid

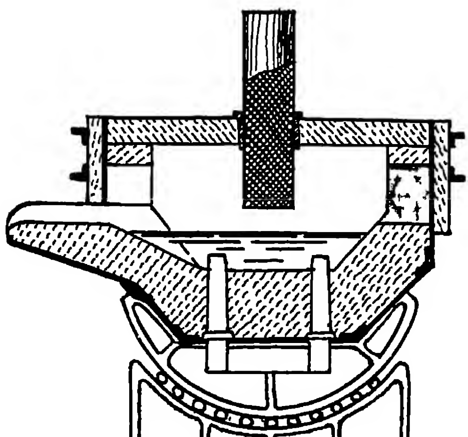


FIG 56—Girod arc electric furnace with one electrode through the lid and water-cooled iron electrodes in the furnace floor

the induction furnace, the first form of which was due to Ferranti (see Fig. 57).

In this case we have a transformer with iron core and primary circuit made as usual. The secondary circuit consists only of a single turn in the form of a fireclay channel lined with magnesite, in which scrap iron or steel is placed. The current induced in it by the variable magnetic flux threaded through it creates heat enough to melt it. We can then add various materials until the charge has its proper constitution.

The production of the so-called alloy steels has assumed

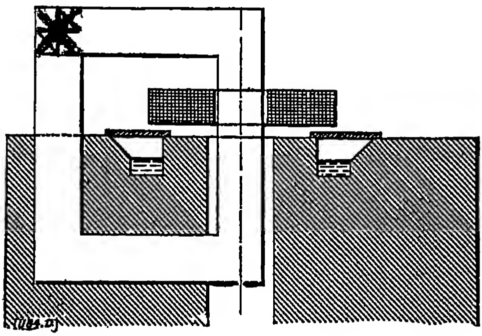


FIG 57 —A diagram representing the construction of an induction electric furnace The white rectangle denotes a laminated iron core which is embraced at one point by a primary coil conveying an alternating current. In a mass of refractory material there is a circular groove which forms the secondary circuit In it the material to be melted is placed

enormous proportions of late years on account of their valuable mechanical and magnetic properties. Such steels as the carbon-vanadium steel or chrome-vanadium steel have the specially important uses in motor car and aeroplane manufacture

As the proportion of the rare metal element is generally very small, it is necessary to prepare, first, a ferro-alloy or alloy of iron with a known large percentage of the rare metal, and then to use the required amount of this fused in an induction furnace with excess of steel to make a homogeneous casting of the alloy-steel.

Thus, for instance, a bar of Swedish iron has an elastic limit of 26,800 lb. per sq. in. and a contraction in area of 50 per cent. before breaking. If alloyed with 0·85 per cent. of vanadium the elastic limit rises to 45,120 lb. per sq. in., and a contraction of 72 per cent. Taking a pure carbon steel the same figures are 67,000 lb. per sq. in. and 7 per cent. contraction. Alloyed with 0·58 per cent. vanadium it rises to 144,800 lb. per sq. in. and a contraction of 7·6 per cent. In vibration it is equally remarkable —a pure carbon steel broke after forty blows. Then it was annealed and broke after 250 blows. Vanadium steel required 500 blows.

Vanadium steel has been called the master weapon of the mechanical engineer.

Of late years, an advance in the structure of induction furnaces has taken place, consisting in the use of high-frequency primary currents and no iron core. The result is to increase the energy efficiency of the appliance.

The possibility of using high frequency in induction furnaces was demonstrated in 1905 by Schneider, but no advance was made until Northrup, in 1919, published a Paper on the subject, and now, in 1926, high-frequency electric furnaces are in use which can deal with 600-lb. charges of nickel alloys. Such a furnace requires no iron core, and consists merely of a helix of copper tube, the turns of which are separated by some refractory insulator. The tube is kept cool by water sent through it. The charge to be melted is placed in a crucible inside the helix. It was necessary then to devise as follows a suitable generator for creating high-frequency electric currents (see Fig. 58). Two large water-cooled electrodes or metal spark balls are included in a chamber containing mercury and means for dropping in alcohol. The discharge from a large condenser, placed in series with the furnace coil, is passed across the gap, the condenser is charged by an alternating voltage of 6,600 volts at 80 frequency, and this discharge consists of damped high-frequency currents of a power equal to 35 to 40 kw. or about 60 horse-power.

Also, high-frequency alternators, having a frequency of 5,000 and voltage of 300, have been tried with good effect, sufficient for a 225-lb. furnace.

An important application of this type of high-frequency furnaces is in the manufacture of nickel-iron alloys, such as permalloy, and the makers of this alloy in U.S.A. have established forty or more furnaces of this kind, capable altogether of dealing with some tons of alloy.

The cleanliness and ease of control of the temperature

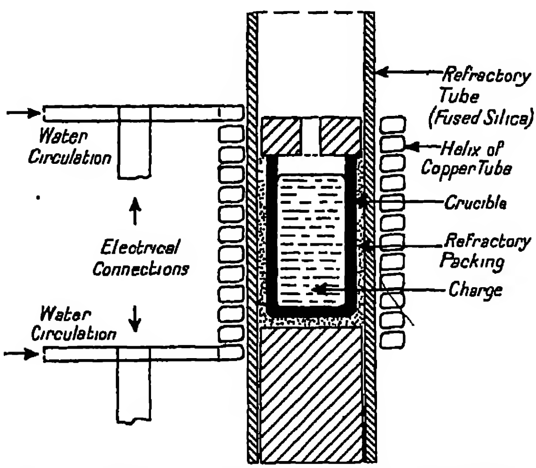


FIG. 58 —Section of a high-frequency electric furnace.

renders the high-frequency induction furnace ideal for preparing alloys with rare or costly metals and for the heat treatment of finished products.

We may next consider one or two of those processes of manufacture in which the heat required for the chemical change is produced by passing an electric current through the material itself.

The majority of chemical actions evolve heat when they take place, and in some cases so much so that if the chemical action is once started at one part of a mass it travels through it rapidly as, for instance, in the

reduction of iron oxide by metallic aluminium or in the explosion of gunpowder.

A few actions, called endothermic, such as the combination of gold and iodine, absorb heat in taking place, and in these cases the action generally requires a high temperature to effect it.

Thus, for instance, carbon will not deprive silica of its oxygen at a low temperature, but it can do so at temperatures approaching 2,000° C.

Amongst important electrothermal industries a prominent place must be given to the graphite, carborundum, and calcium carbide industries, which are closely connected

It is commonly said that the element carbon can exist in three allotropic forms, viz., charcoal, graphite and diamond. Ordinary coke, soot, or anthracite coal, or most organic substances, heated out of contact with air, yield a material which is more than 95 per cent. carbon. If, however, this material is heated to a still higher temperature, about 2,250° C. in an electric furnace, and if certain catalysts are present, such as silica or oxide of iron, the carbon passes into the graphite form, in which it is harder and a better conductor of electricity, and *marks* paper and has a greasy feel. This process is now conducted on an enormous scale for making electrodes for electric arc furnaces, and for crucibles, etc The article to be graphited is moulded out of a paste made of finely-divided carbon produced by burning oil residues or finely-ground coke mixed with sugar or tar. It is then baked and heated. There must be a small percentage of ferric oxide or silica present. The carbon article is then heated to a temperature of 2,000° C. in an electric furnace, and becomes converted into graphite. From finely-divided graphite various forms of lubricant can be made.

This process is conducted on a very large scale near Niagara Falls, in the United States, with electric power derived from the falls. It ought to be conducted on a large scale in Great Britain with cheap power obtained

near coal mines, which would provide both the power and the carbon in the form of coke residues, and render us independent for this manufacture on the enterprise of the United States.

If finely-divided coke, sawdust and sand is heated to 1,950° C. it is converted into carborundum.

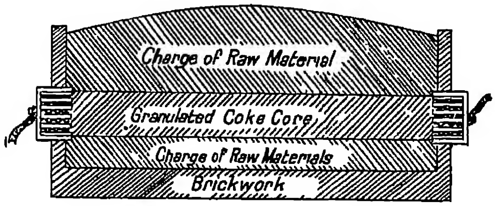


FIG 59 —Electric furnace for converting coke into graphite.

The first to do this, on a large scale, was E. G. Acheson, in 1891, in an endeavour to make diamonds.

The chemical reaction is :—

$$SiO_2 + 4C = SiC_2 + 2CO.$$

The mixture of coke and sand is built into a brick box with a graphite or coke core and a current of 10,000 amperes sent through it. The carbon monoxide gas (CO) burns on the surface, and when the reaction is complete the box is dismantled and the carborundum sorted out, ground, and used for making grinding wheels and cutters (see Figs. 59, 60, 61).

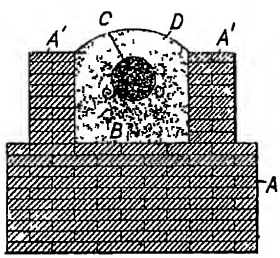


FIG 60 —Section of an electric furnace for converting coke into graphite or manufacturing carborundum from sand and coke

The possibility of producing diamond artificially has been carefully explored by Sir Charles Parsons. Briefly, his conclusions from experiments are that no production of diamond can take place by mere heating or compression of carbon in any form. Diamond is only produced in some matrix of iron or material containing iron, and when carbon monoxide gas is present. It is possible that it results in some way by the substitution

of carbon for iron in the carbide of iron (Fe_3C) known as *cementite*, which plays a great part in the production of hard steel.

Another important electrothermal product of the same kind is calcium carbide (CaC_2), obtained by heating lime and powdered coke to a temperature of 2,000° C. or so by electric heating.

The reaction is $CaO + 3C = CaC_2 + CO$.

The calcium carbide acted on by water gives acetylene,

$$CaC_2 + 2H_2O = CaH_2O_2 + C_2H_2.$$

C_2H_2 is used for oxy-acetylene welding. If calcium

FIG. 61—The brick box or furnace in which carborundum is manufactured, dismantled after the conversion is complete.

carbide is heated with nitrogen gas, produced from liquid air, we obtain a valuable fertiliser, called calcium cyanamide ($CaCN_2$), and this, under the action of water, evolves ammonia, lime and CO_2, according to the equation :—

$$CaCN_2 + 4OH_2 = CaH_2O_2 + CO_2 + 2NH_3.$$

Nine hundred thousand tons of calcium cyanamide are now manufactured per year, more than *half* of which is made in Germany. Calcium carbide is now chiefly manufactured for making this amide.

Electrolysis is also used as a means of preparing caustic soda from a solution of salt. The free sodium liberated at the cathode forms with water sodic hydrate. Chlorine

gas, which can be used for making bleaching powder, is also given off at the anode. In making these products a porous diaphragm must be used, which allows the electric current to pass, but keeps the solutions near the anode and cathode separate and prevents the free chlorine gas from recombining with the sodic hydrate. The sodic hydrate can be converted by heat into caustic soda (Na_2O). The hydrogen gas liberated at the anode by the action of the sodium on the water, is collected and used for filling airships or for other purposes.

In the same way, caustic potash is prepared from potassic chloride found native in the Stassfurt and Alsatian salt deposits.

Metallic sodium is now prepared on a large scale by electrolysis of fused sodic hydrate, which is exactly the process by which Sir H. Davy discovered sodium more than 120 years ago at the Royal Institution of Great Britain.

There is hardly any other department of electrical research likely to yield more immediate practical results than that directed to electro-chemical and electro-metallurgical problems. There is an enormous loss of such easily oxidised metals as iron due to rust or oxidation, and in the case of tin there is a shocking dissipation of our world store by mere waste. Tin is used to coat sheet steel and so prepare so-called sheet tin used chiefly for canisters for preserving food, and also in the form of tinfoil for preserving various confections and edibles. It is so used because it is non-poisonous and not easily oxidised, but the greater part of the tin thus used is thrown away and lost.

We are, therefore, faced with the possibility of a tin famine, and in the same way with other metals, such as lead, fired away in bullets and shot and finally lost.

The problem of preparing aluminium electrically and cheaply from ordinary clay is, therefore, of primary importance, as it is certainly the metal of the future. It is ductile and can be rolled into thin sheets and easily melted and cast.

The problem of preparing from ordinary clay the aluminic silicate and converting this into the oxide is a purely scientific research matter, but one the solution of which will have extremely valuable practical results in connection with common life as well as electrical engineering It is, however, essential that the aluminium shall be extremely free from impurities if it is to remain uncorroded. The ease with which it is tarnished or attacked by alkaline liquids depends on its purity. Thus aluminium containing only 1 per cent. of zinc corrodes seventy times as fast as the absolutely pure aluminium.

CHAPTER VIII

ELECTRICAL MEASUREMENT

In this final chapter the subject we shall consider is the relation of scientific research to industrial electrical measurements. The late Lord Kelvin once said that any branch of knowledge only becomes science just in proportion as it becomes the subject of exact measurement.

Lord Kelvin's precise words were as follows (*Popular Lectures*, Vol. I., p. 73) :—

"I often say that when you can measure what you are speaking about and express it in numbers, you know something about it ; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind ; it may be the beginning of knowledge, but you have scarcely advanced to the stage of science"

Judged by this standard, electrical knowledge is highly scientific, because in hardly any other branch of physics can more exact measurements be made. This state of affairs is, however, of somewhat recent growth. We have only to look back at some of the older books on Electricity and Magnetism to notice the comparative paucity of numerical results or the empirical mode in which they are stated and the arbitrary units employed.

One of the earliest pioneers in exact scientific electrical measurement was that strange recluse, Henry Cavendish, a scion of the house of Devonshire, who lived between 1731 and 1810, and whose electrical work was mostly done about 1773. He was a careful and most exact experimentalist, but he had a curious reluctance to publish his results (so different from us) and much of it remained

unknown until Clerk Maxwell, between 1874 and 1879, examined, expounded, and collected in a single volume these remarkable researches at the instance of the then Duke of Devonshire.

Cavendish had arrived at a clear notion of the electrical capacity of a conductor or condenser as a measurable quantity, and expressed it in "inches" by comparing it with the capacity of a sphere whose diameter was 12·1 in. Thus all his results are directly comparable with our present day measurements in electrostatic units, since in these last units the capacity of a sphere is numerically equal to its radius in centimetres. Cavendish measured the capacity of condensers formed of slabs of various insulators of the same thickness, coated over equal areas on both sides with tinfoil. This enabled him to anticipate Faraday in the discovery of the "specific inductive capacity" of these different insulators. For glass, shellac, and beeswax he gave numerical values of their dielectric constant, as we now call it, viz., 8·2, 4·47, and 3·5 respectively, that of air being taken as unity.

Furthermore, Cavendish had some idea that conductors differ in the quality we now call resistance. He arrived at numerical results by the rather rough process of taking "shocks" from a condenser through the conductors in question, such as a long iron wire or a column of water, and adjusting the conductors or the condensers until the shocks in the two cases were judged to be equal. When his own judgment was at fault a servant called "Richard," was called in, and "shocks" administered to him on which he had to give an opinion as to their equality or inequality. We are not told how far Richard enjoyed being made use of as a sort of ballistic galvanometer or shock meter.

Cavendish also made another very remarkable quantitative measurement, which was carefully repeated by Clerk Maxwell at the Cavendish Laboratory. The object of this was to determine how far the law of electric attraction or repulsion of two small electrified particles differed from the exact inverse square of their distance. He

proved this by an experiment with the aid of two concentric spherical conductors, and deduced that the exponent of the denominator does not differ from 2 by as much as $\frac{1}{50}$th. Maxwell repeated the experiment with a far more sensitive quadrant electroscope, and showed that the exponent did not differ from 2 by as much as 1 part in 21,600.

There is clear evidence that Cavendish, in 1781, anticipated Ohm in the celebrated law given by the latter in 1827, viz., that when temperature changes are excluded the current flowing through a metallic conductor is exactly proportional to the potential difference of the ends.

Although Cavendish did not employ our technical phrases, there is abundant proof that the idea conveyed to us by the word "potential" was quite familiar to him.

It may be remarked in passing that a great part of the growth of science is dependent on progress in making clear definitions of the quantities to be measured and inventing suggestive words or expressions for them. The older electricians employed the terms, quantity and tension, in a vague sense. Tension expressed the tendency on the part of electricity to escape from some place without any clear idea of where it wanted to go. It was many years after G. S. Ohm, in his essay, *Die Galvanische Kette mathematisch bearbeitet*, first gave the definite relation of current, electromotive force, and resistance in an electric circuit, before the exact ideas now conveyed by these terms were clearly formed on the minds of electrical workers generally. Moreover, when they were formed the measurement of them was expressed in terms of certain arbitrary and unconnected physical standards. The unit of resistance was the resistance of a particular bit of wire, and electromotive force that of a particular type of voltaic cell.

The conception that electrical units should be related to each other and to the mechanical units, through the common ideas of work and power or rate of doing work

was first put forward by the German physicists, W. Weber and K. F. Gauss, of Gottingen, in connection with their magnetic measurements. This absolute system was brought into notice in Great Britain by the late Lord Kelvin, and at his suggestion the British Association Committee on electrical units was formed in 1861 to construct standards or units and determine their value in terms of the absolute units. After discussion and some differences of opinion, the centimetre, gram, and second (c.g.s.), were selected as primary units of length, mass and time.

Since there are mechanical forces between electric charges and also between magnetic poles and, therefore, work done in separating or approximating them, we start with two systems of units, but these are interrelated by the fact that between moving quantities of electricity and magnetic poles stresses exist. Accordingly, we have the electrostatic and the magnetic systems of derived units, and the relation between corresponding units is always some power of a velocity. This velocity is the reciprocal of the square root of the absolute value of the dielectric constant and magnetic permeability of the medium in which the experiments are conducted. The first determination of the value of this velocity was made by Weber and Kohlrausch in 1856, and in air was found to be near to 3×10^{10} cm per sec. Kirchhoff pointed out that this was nearly the value of the velocity of light in centimetres per second The true meaning of this agreement was not understood until more than nine years later, when Maxwell expounded his electromagnetic theory of light.

As the units in these two systems were not found to be of a convenient size, a third system of practical units had to be created out of decimal multiples or fractures of the absolute units on the magnetic system, and these, as we know, are named after famous men.

Even then we are not at the end of complexities, and a fourth system of rational units was proposed by the late

Mr. Oliver Heaviside to get rid of an ubiquitous 4π, which intrudes itself to the perplexity of students into certain common equations. Thus, if E is the electric force between the plates of a plane condenser of which the dielectric has a thickness t and area A, and a dielectric constant K, then $E = V/t$ if V is the potential difference of the plates, and if ρ is the surface density of electricity on the plates, $\rho A =$ total quantity of electricity $= Q = CV$ or $\rho A = CEt$, but E can be shown to be equal to $4\pi\rho$, therefore $C = \dfrac{A}{4\pi t}$ and $Q = CV = DA$, or $D = \dfrac{KE}{4\pi}$.

We can only exclude the 4π from this equation by defining the unit of electric force not by quantity divided by square of distance, but by quantity divided by $4\pi \times$ square of distance, or making the electric force due to a quantity Q at distance d, $\dfrac{Q}{4\pi d^2 K}$ and not $\dfrac{Q}{d^2 K}$.

If, then, D is the displacement or effect of the electric force, $Q = 4\pi d^2 D$ and $D = KE$.

These rational units have not come into general use because it would necessitate altering all our resistance coils condensers, etc., in common use to realise them.

The determination of the absolute value of the practical c.g.s. units has given rise to an enormous amount of exact quantitative research.

The B. A. Committee constructed a number of resistance coils of various kinds of alloys in the form of wires. These were adjusted to represent what the Committee then thought were 10^9 electromagnetic absolute units of resistance. These coils had marked on them the temperatures at which they were said to be, 10^9 such units.

As a matter of fact, they did not represent 10^9 c.g s. electromagnetic units (E.M.U.), but, as proved by Lord Rayleigh and others, only 986·5 million c.g.s E M. units. In other words, they were too small by about $1\frac{1}{2}$ per cent.

Moreover, changes in the alloys had made them all different in resistance at the marked temperatures.

Observations made by the author, in 1880, determined

the most probable value of the B. A unit, and Lord Rayleigh and others determined its absolute value.

The scientific standard of reference is now the resistance of a column of pure mercury 1 sq. mm. in section at 0° C., and the best results show that a column 106·245 cm. in length has a resistance of 10^9 cm. per sec., or 10^9 c.g.s. units.

In actual practice the standard of resistance is always that of a wire, generally constantan or manganin, which is adjusted to be of a resistance at some stated temperature to the 10^9 equivalent to 10^9 cm. per sec.

The so-called International Ohm is the resistance of a column of mercury, 106·3 cm. in length and weighing 14·4521 gm. at 0° C. and of constant cross-section.

Hence, even the accepted International Ohm is not exactly 10^9 c.g s. units. We are in this respect as with the length of the metre. This unit is not $1/10^7$ of an earth's quadrant in length, but is the length of a standard bar kept at Paris.

It will not be possible or necessary to describe all the methods for determining the value of a resistance in absolute measure, nor the methods of comparing resistances. These are given in all good text-books, but reference may be made to Vol. II. (Electricity) of Sir Richard Glazebrook's *Dictionary of Applied Physics*, which contains very valuable articles on *Electric Units* and *Electric Measurement*.

In connection with electrical engineering work, the provision of means for measuring large currents and electromotive forces is very important, and this must often be done by some method which can be operated at a distance.

This has been achieved by the so-called potentiometer method, now in such extensive use

When a current flows through a uniform wire there is a steady fall of potential down it. If any source of E M.F., say, a voltaic cell, has its terminals connected to two points on the wire, in such way that the fall in potential

due to the current in the wire opposes the E.M.F. of the cell, the cell will give no current as shown by a sensitive galvanometer in its circuit. The potential fall down the wire is proportional to the length of intercepted wire. So we can compare the E.M.F. of two cells in this manner.

This method was used by Mr. Latimer Clark and called the potentiometer method. The late Lord Rayleigh had shown that in place of a cell we might balance the drop in potential due to a large current flowing through a low resistance.

This mode of working merely gave arbitrary ratios and was not convenient as a workshop method.

In 1882, when the author was appointed scientific adviser to the Edison Electric Light Company, of London, and subsequently of the Edison and Swan Electric Light Company, the necessity for quickly measuring voltages of about 100 volts and currents of large value was pressed upon him.

Accordingly, he modified this potentiometer method to make it direct reading. The author adopted a standard cell, viz., an improved Daniel cell, of which the E.M.F. was near to 1·07 volts. A rheostat was placed in series with the potentiometer wire to adjust the current, and alongside the wire a scale divided into 2,000 parts. The standard cell was then connected in and the current varied until the E.M.F. of the cell was just balanced, when the cell was connected in between divisions 0 and 1,070 on the wire. This was called "setting the potentiometer." Then, to measure any other E.M.F. less than 2 volts the balance could be obtained at another point and the E.M.F. read off directly on the wire. To measure large currents a low resistance of known value and large current-carrying capacity was made by placing in parallel a certain number of platinoid wires, each of 1 ohm resistance. This method was first described by the author in an extinct journal, called *Iron and Industries*, in 1884.

In 1885 or 1886, Messrs. Crompton, of Chelmsford, began to make ammeters and voltmeters, and at Colonel

Crompton's request the author set up at their works a potentiometer, made as above described, for calibrating these instruments in terms of a Clark cell, which proved better as a standard than the Daniel cell and was more portable. The method of measuring large voltages was by the use of a divided high resistance wire, which afterwards came to be called a *volt box ;* and for the measurement of large currents low strip resistances of manganin came into use.

Instrument-makers then began to copy this arrangement, and innumerable forms of direct-reading potentiometer, on the above plan, were made. The Clark cell has, however, an E.M.F. which has a large temperature variation, and in spite of the considerable amount of research bestowed on it by Lord Rayleigh and others, it has now been replaced by the Weston cell, invented in 1892, of which the elements are mercury, mercurous sulphate, cadmium sulphate, and cadmium, which has a negligible temperature variation and an E.M.F. at 20° C. of 1·0188 volts, or $1{\cdot}0188 \times 10^8$ c.g.s. E.M. units.

Although the standard of resistance, viz., 1 international ohm, and the E.M.F., the international volt provide also the unit current, viz., 1 ampere, yet immensely extended researches have been made to determine the ampere in terms of the electrochemical equivalent of silver.

The international ampere is defined to be the current which deposits from a neutral solution of silver nitrate, made according to a certain specification, silver at the rate of 0·00111800 gm. per sec.

These definitions and international standards have only been reached after an enormous amount of scientific research into the causes of variations, but the result has been to provide electrical engineering with a most exact and universal set of practical units and appliances for measurement.

Hence the performance of electrical engineering appliances, such as dynamos, motors, transformers,

batteries, etc. is now capable of precise determination and specification.

Moreover, as power in the form of an electric current supplied at a certain voltage is a marketable commodity, it necessitates control over the accuracy of the house meters used for its measurement. Recognising, as far back as 1885, the need for an authoritative standardisation, the author read a Paper to the Institution of Electrical Engineers, of London, entitled, "The Necessity for a Standardising Laboratory for Electrical Test Instruments." One outcome of that Paper was that the Board of Trade established a small Testing Laboratory at Richmond Terrace, Whitehall, for this purpose. The late Major P. Cardew was the first Director and Mr. A. P. Trotter succeeded him. Subsequently, a more ambitious scheme was launched in the National Physical Laboratory, at Teddington, in which physical researches were carried out on a scale impossible for private individuals, and official tests made on all kinds of physical appliances.

The result has been to bring about a remarkable improvement in technical work and unquestionable accuracy in all the meters and measuring instruments involved in electrical engineering work. But for these authoritative tests and irreproachable standards endless disputes would have arisen and great confusion.

In all parts of the work scientific research and technical applications have advanced hand-in-hand.

Consider the development of simple ammeters and voltmeters for direct current (D.C.) measurement. By far the larger part of these are moving coil instruments, in which a magnetic field is provided by a permanent steel magnet in the field of which the coil is rotated by the current against the force of a spiral spring of some kind. If the instruments are to retain their accurate calibration, then the field of the magnet must remain constant against its own self-demagnetising power and the reaction of the current in the coil. This has involved a vast amount of research to find the best type of magnet steel and the best

methods for bringing the magnet into a settled-down or permanent condition. It has required the co-operation of metallurgists and steel manufacturers as well as physicists.

Steels differ extremely, not only in magnetic susceptibility, which determines the intensity of magnetisation under a given magnetising force, but in magnetic stiffness, which determines the degree to which they can retain it against de-magnetising force. Certain elements, such as tungsten in about 5 to 10 per cent. in steel, greatly increase magnetic stiffness, and other alloy steels, such as the cobalt-chrome steel, have even greater magnetic stiffness. A final heat and mechanical treatment is necessary to bring the magnetised steel into a stationary condition.

Reference has been made in Chapter II. to two very comprehensive Papers by Mr. S. Evershed on Permanent Magnets,* which contain a large amount of information on this subject. The construction of *permanent* magnets is, in fact, the essential element in all types of direct-current ammeters, voltmeters, ampere-hour and watt-hour meters.

In all the recording instruments there is a sort of armature which revolves in the field of a magnet or field of a current coil. It is coupled to a copper disc which revolves between the poles of another magnet. The driving force is proportional either to the current in ampere-hour meters or to the power in watt-hour meters. The retarding force is proportional to the speed. Hence, the quantity of electricity or the quantity of energy which has passed through is proportional to the number of revolutions of the armature. In these, as also in the "Meggers" for measuring insulation resistance, the calibration depends on the permanence of the magnets.

In alternating current measurement we are concerned with two other measurable quantities, which need standards and methods of measurement. These are capacity and inductance. For standards of capacity we

* See *Journal, Institution of Electrical Engineers*, Vol 58, p. 780, and Vol 63, p 725.

must make use of air or vacuum condensers, of which the absolute value can be best determined by some form of commutator which charges the condenser at a known voltage and discharges it through a galvanometer a known number of times per second. A tuning-fork, electrically maintained, was at one time used as a commutator, but a far better device is the rotating commutator devised by the author and Professor Clinton. We can eliminate the measurement of voltage by using the same E.M.F. to calibrate the galvanometer or by a bridge method. A condenser, plus a commutator, is, in fact, the equivalent of a resistance. A vast number of bridge methods have been devised for the measurement of inductance, and it may be determined in terms of a capacity and a resistance squared, or product of two resistances. The dimensions of inductance on the electromagnetic system of units is a *length*, and it is therefore expressed as so many centimetres. The dimensions of a capacity in the same system is a length divided by the square of a velocity and the dimensions of resistance is a velocity. Hence, an inductance is the equivalent of a capacity and the product of two resistances.

In alternating current measurements we are troubled with three sources of error. In the first place, the formulæ or methods we are employing may depend upon the E.M.F. having a simple sine curve variation which is difficult to secure. In the next place, our means of detecting the equality of potential of two points are far less sensitive than for direct current and, moreover, may depend upon an equality in phase as well as amplitude. Thirdly, we have especially to guard against error due to the unknown self-capacity or inductance of resistance coils or other parts of the circuit. This last is a fruitful source of error in high-frequency measurements.

As sources of alternating currents we have (i.) vibrating interrupters, hummers, or tuning-fork commutators, none of which can be depended upon to give true sine-curve E.M.F., but often vastly different. A rough test

of the sine curve purity is to employ it to charge a condenser and measure the current. For pure sine curve E.M.F. (= E), the current A is $A = 2\pi n EC$, where C = capacity and n = frequency.

Then (ii.) we have specially constructed alternators to give sinoidal E.M.F. These are generally expensive and have a small range of frequency.

(iii.) We have the thermionic valve oscillator and Vreeland mercury arc oscillator, which give a fairly pure wave form and considerable range of frequency.

As detectors we have (i.) the electro-dynamometer, with or without iron core; (ii.) the vibration galvanometer; (iii.) the rectifier plus ordinary galvanometer; (iv.) the telephone; (v.) the thermionic detector.

The theory and improvement of each of these has been the subject of an enormous amount of research, as well as the investigations which have led to methods for measuring self and mutual inductance, capacity, alternating current resistance, power absorption with alternating circuits, and dielectric constants, power factors and hysteresis. The best account of all these methods and a most copious reference to original scientific Papers is to be found in Vol. II., *Electricity*, of Sir R. Glazebrook's *Dictionary of Applied Physics*, in an article on Inductance, by Mr. A. Campbell. The application of all this knowledge in electrical engineering has been very extensive. One of the first was in the construction of alternating current ampere-hour house meters.

For this purpose the repulsion principle explained in the second chapter is utilised. The eddy currents set up in a pivoted copper disc by the current to be metered passed through coils either without or with divided iron cores, causes a rotation of the disc, and then a retardation proportional to the speed is created in the disc by permanent magnet poles embracing it. The electrodynamo meter or watt meter principle is also used, and with suitable precautions the coils, as in Dr. Sumpner's instruments, can be wound on iron cores.

For the direct measurement of alternate current the dynamometer principle, as used in Lord Kelvin's ampere balances, is perhaps the most exact, and these admit of easy calibration by direct currents. Commercial instruments work on the same principle, but the magnetic fields due to the fixed coil can be strengthened by the use of short-divided iron cores, provided the magnetic circuit has a large air gap portion, so that the part of the magnetisation curve used is practically a straight line sloping upwards at a constant angle.

In the measurement of alternating voltage the electrostatic attraction principle is nearly always employed. If a multiplate condenser has one set of plates fixed and the other movable, being suspended by a torsion wire or pivoted and restrained by a spring, then, on giving the plates an alternating potential difference the movable plates try to move in between the fixed plates so as to diminish the potential energy. Since the attraction between such plates is proportional to the square of the potential difference, the calibration of the scales is never equidivisional but may be made approximately so over a certain range by giving the movable plates a particular shape.

A large class of electrical measurements which have, of late years, become of very great importance, are those connected with high-frequency currents and wireless telegraphy and telephony.

It is, in fact, remarkable to notice the manner in which applications of scientific discoveries and research suddenly convert very abstruse or difficult physical measurements into a matter of as much public interest and importance as a grocer's scales or a linen draper's yard measure.

Thus, before about 1904, next to nothing was known about the measurement of wave lengths of electric waves used in wireless telegraphy. Only very rough guesses were possible as to the wave lengths used in early experiments in wireless telegraphy. Now we have International Commissions sitting to fix and determine them and

legislation imposing penalties for trespassing into forbidden wave lengths. The author was one of the first to make an instrument, called a Cymometer for this measurement, described to the Royal Society of London in 1905.

In connection with this part of the subject we have to employ special appliances for the measurement of the very small or very large high frequency (H.F.) currents and high-frequency voltages used. Also the measurement of high-frequency resistances involves different processes from the simple bridge methods possible in direct current measurement. The capacity and inductance of short lengths of wire, or due to the proximity of conductors, which would be quite negligible in the case of direct current measurement, becomes of very great importance in high-frequency measurement. Moreover, inductance and capacity are not necessarily separated. Inductive circuits have self capacity, and condensers are inserted in circuits having some inductance.

The recognition of this fact and the objections to this concealed capacity in wireless apparatus has led to a large number of inventions for winding inductance coils so as to eliminate the capacity between turns as far as possible. Even now, inexperienced persons are oblivious to some of its effects and will connect loud-speaking telephones to a distant receiver by long lengths of rubber-covered twisted flexible wire. The high capacity between the wire then shunts off the higher harmonics and causes distortion of the sounds. Formulæ were given long ago by the late Lord Rayleigh and Lord Kelvin, enabling the high-frequency resistance of round straight wires to be predetermined, but theory and experiment show that there is an added resistance when the wire is spiralised or wound round an iron core as in a telephone receiver or in proximity to other conductors, and in the majority of cases the predetermination of the high-frequency resistance is impossible, and it can only be discovered by experiment. For frequencies within an audition range the Heaviside bridge can be conveniently employed, the high-frequency

currents being provided by a thermionic oscillating valve and the potential detector being a vibration galvanometer, tuned for the frequency used in the supply. In the case of radio frequencies the only satisfactory method is the substitution in which the damping produced by the circuit under test is imitated by the use of a variable resistance, which is the same for direct and high-frequency currents, and can, therefore, be determined exactly.

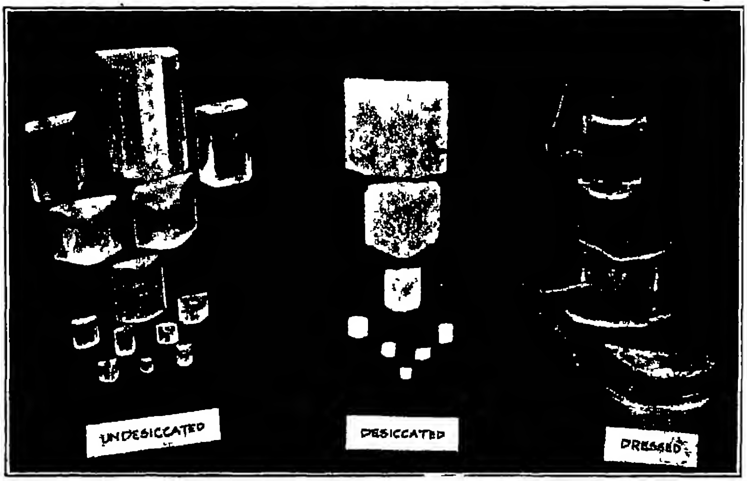
In wireless work two very special measurements are required, viz., those of wave length and wave amplitude or signal strength. The former is generally determined from the frequency, since the product of wave length in metres and frequency is the numeral value of the ether wave speed in metres per sec., which is 3×10^8 m/s.

The determination is nearly always dependent on tuning a weakly-coupled circuit of known and variable capacity and inductance and using some detector, such as a neon tube or glow lamp or telephone, to decide when the two circuits are in exact resonance. In the author's cymometer a neon tube is used as a detector of the point of resonance of the two circuits. In the cymometer the inductance and capacity both vary together, so that the square root of their product varied proportionately to the wave length λ, and the latter is measured at once by a factor multiplying the product $\sqrt{CL}$. The exact calibration of wave meters is an important matter, as, owing to the enormous multiplication of transmitting stations and tuned receivers, great exactness and constancy in wave length must be maintained.

In this connection a highly interesting application of pure scientific research in technology is the use now made of piezo-electric crystals in wireless work.

It has been known for many years (certainly forty-five) that certain hemihedral crystals become electrified by pressure. But it was discovered by M. M. Curie that crystals of quartz, or of Rochelle salt, which is double tartarate of potassium and sodium, have the curious property of expanding and contracting in electric fields, and that these

changes of size can take place with enormous rapidity under an alternating E.M.F. Simultaneously, the contractions and expansions develop charges of electricity, positive and negative, on the faces. If a slice of quartz crystal is cut with one long side in the direction of the optic axis and two other rectangular axes perpendicular to the flat face and to one thin side, then if this crystal is placed between metal plates, which can be electrically



By courtesy of Mr E Kilburn Scott

FIG 62.—Piezo-electric crystals of Rochelle salt

charged, the slab will expand and contract along these two active axes when subjected to an electric force.

The crystal has a natural fundamental rate of expansion, but it can also vibrate at other rates, which are harmonics of the fundamental. If the crystal slice is inserted between metal plates, but left free to expand, then it constitutes a condenser, which will pass a maximum alternating current when this current has the natural frequency of the crystal, but for any other rates it acts as a high impedance. It is quite possible to cut a crystal which will have a natural frequency of a million or more (see Fig. 63).

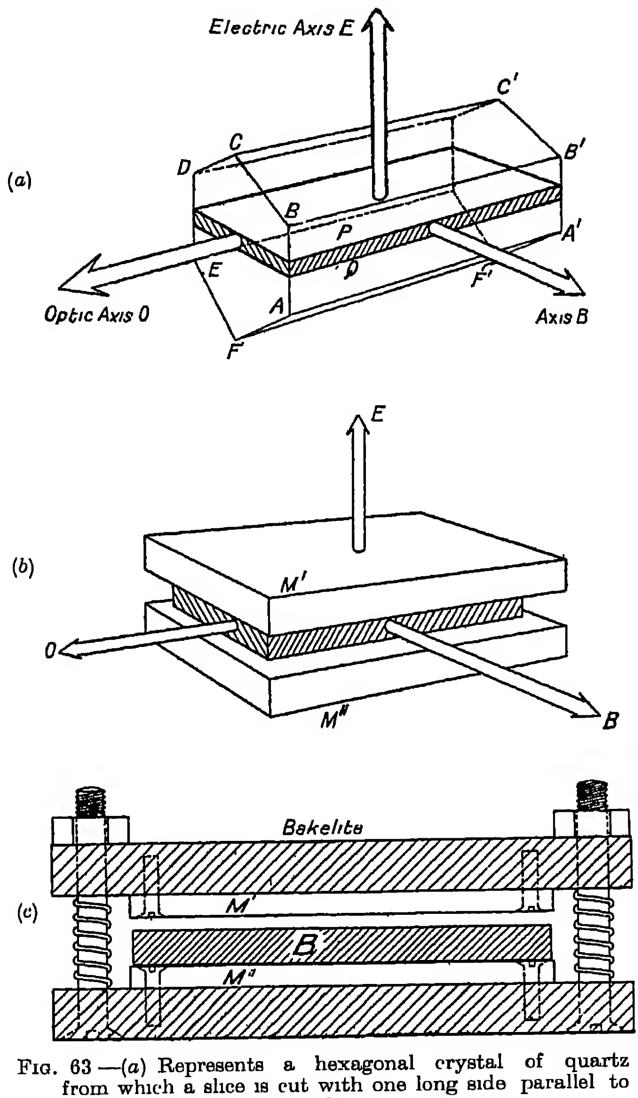


FIG. 63 —(a) Represents a hexagonal crystal of quartz from which a slice is cut with one long side parallel to the optic axis of the crystal

(b) This crystal slice is mounted between two metal plates so as to form a condenser.

(c) But the metal plates do not quite touch the slice but leave it room to expand freely.

In a long and useful paper, published by Mr. D. W. Dye, describing a research on the quartz crystal resonator, it was pointed out that, electrically considered, such a crystal condenser is equivalent to a capacity in series with an inductive resistance, the two being shunted by another capacity. Such a system has its own natural frequency of oscillation, and for this frequency in an applied E.M.F. the current passed is a maximum.

Accordingly, the crystal condenser can be used to obtain and fix a standard frequency. For, if it is shunted across a condenser in series with an inductance the frequency period of which can be varied, then there will be a marked drop in the current in that resonant circuit when the tuning just matches the natural frequency of the crystal.

It has then been found that such a piezo-electric crystal, as it is called (from the Greek verb πιέζω : I press) can be used to control exactly the frequency of a thermionic oscillator. It is then called a *Stabilizer*. For, if such a crystal is interposed between a source of high-frequency current (say, a valve) and a power amplifier, the crystal will only pass sufficient current to operate the amplifier at the exact frequency for which the crystal is cut. Hence it acts as a very exact wave filter, and it can be used to stabilise or keep exact the frequency of output.

Also, as Professors W. C. Cady and G. W. Pierce have shown, the natural frequency of the crystal mechanical oscillations can be used to calibrate wireless wave meters with great accuracy. Pierce has combined a piezo-electric quartz plate with a three-electrode thermionic valve in such way as to give a standard and invariable electric oscillator which acts for electric oscillations like a standard tuning-fork for aerial or sound waves. These applications of pure research on the electrical piezo properties of crystals are of great practical importance in wireless telegraphy and, perhaps, also in other branches of technology. The measurement of radio-frequency

and its control becomes by means of these crystals, one of the most accurate which can be made.

Professor G. W. Pierce has, for instance, applied the quartz-valve resonator to the measurement of the velocity of sound with remarkably interesting results. Also, Pierce has devised arrangements by which the absolute period of the crystal can be determined in terms of a standard tuning-fork and a standard clock.

This also implies that measurements of length and expansions and temperatures can now be determined with extraordinary accuracy.

The reader who desires more information on the subject of this Piezo-Electric Quartz Resonator may be referred to a very comprehensive and exhaustive paper by Mr. D. W. Dye in the *Proceedings of the Physical Society of London*, Vol. 38, August, 1926, p. 399. This extensive work was carried out at the National Physical Laboratory, England.

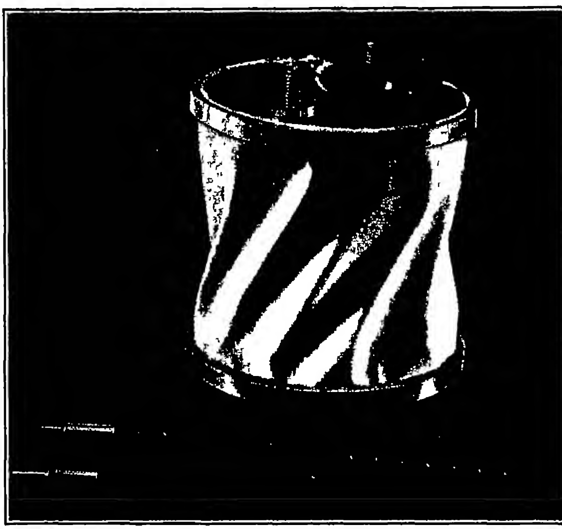
Also, reference may be made to two Papers by Professor G. W. Pierce in the *Proceedings of the American Academy of Arts and Sciences*, Vol. 59, October, 1923, and Vol. 60, October, 1925, and to a Paper by Mr. E. Kilburn Scott, in the *Transactions of the Faraday Society*, Vol. XVII., May 1922, on the Piezo-Electricity of Rochelle Salt Crystals.

In this last-mentioned paper are given some very extraordinary facts connected with the piezo-electric properties of Rochelle salt discovered by Mr. A McLean Nicolson in the research laboratory of the American Telegraph and Telephone Co., New York City, U.S.A.

During the last three years electric waves of accurately known frequency have been sent out from a radio-station at the National Physical Laboratory on the advice of the Radio Research Board of the Department of Scientific and Industrial Research to provide a means for accurately calibrating wave meters. At present, a long programme of waves of lengths 200 to 960 kilocycles per second is sent out at certain times and days.

In addition to wave length another radio-measurement

of great importance is signal strength and the relative strength of just detectable and good commercial strength signals and "atmospherics" at various times. This is now determined and expressed in terms of the maximum or R.M.S. value of the electric field which must exist at the receiver reckoned in microvolts per metre, which is the



By courtesy of Mr E Kilburn Scott

FIG. 64 —A piezo-electric Rochelle salt crystal is mounted between two metal plates and these are connected by a corrugated paper tube The crystal is so cut that the optic axis is the axial line Any vibrations due to sounds created near the paper diaphragm then excite electric potential differences of the plates in contact with the crystal.

same number as electric field strength in absolute electromagnetic units.

Now that very large radio-stations have been erected in numerous places, costing immense sums of money, it has become of supreme importance to have accurate methods of comparing the results in different places.

In these undertakings we have three elements con-

cerned. There is, first, the transmitting station, and we wish to know how much of the power expended is emitted in the form of electric waves of a desired wave length. Then, secondly, there is the space transmission, and we wish to know how much of the wave power emitted from the station close to it is absorbed by any associated receiving station, and the rate at which it decreases with distance. Thirdly, we desire to know what this absorbed radiant power must be to give comfortable and easily recorded or read signals at all times of day and night and at quiet and disturbed times of "atmospherics" to give good commercial communication.

The power supplied to the radio-station can be measured by well-known methods. The power given to the aerial is the product of the square of the aerial current (A) and the sum of the aerial ohmic (r) and radiation resistances (ρ), which can be measured and calculated. The efficiency of the station is then the ratio of ρA^2 to the total power given to it.

Supersonic waves

The radiation resistance is $\rho = 1{,}600 \dfrac{h^2}{\lambda^2}$, where h is the the effective height of aerial and λ is the wave length. Also, $h = \dfrac{E\lambda d}{337A}$, where A is the sending aerial current and E the field in microvolts per metre at a distance d. Now E can be measured, and, hence, h found and, hence, the radiated power.

The laws according to which the wave amplitude diminishes with distance over sea and land have been the subject of an immense amount of research. The attenuation has been in many cases found to agree approximately with an empirical formula given by Austin, which gives the current in the receiving aerial A_r of height h_2 in terms of that of the sending current A_s in aerial of height h_1, such that $A_r = A_s \dfrac{377 h_1 h_2}{\lambda d R} \epsilon^{-\frac{\cdot 0015 d}{\sqrt{\lambda}}}$

But this is merely an empirical formula.

In 1923–24 the French Compagnie Générale de T.S.F.

carried out researches at the transradio-receiving centre at Villa Elisa, near Buenos Ayres, made on waves from New York, Sainte Assise, Bordeaux, and Honolulu. The waves from N. and N.E. gave a figure near to that by Austin's formula. Waves from the West over the Pacific were stronger than that given by the formula. Hence, all that can be said is that the formula gives a rough indication of the received current likely to be obtained in a receiver of known resistance R and height of aerial h_2.

It would occupy far too much space to go in detail into the methods of measuring signal strength and electric force at the receiving station. Suffice it to say that one of the simplest methods is to employ a frame aerial and to determine the E.M.F., which must be artificially created in this aerial of the frequency of the incoming wave to produce the same signal strength on the detector and amplifier used. Very great precautions are necessary to avoid disturbances and errors, but the method seems capable of giving reliable results, especially if two frame aerials at right angles are used, as done by Vallauri, one to receive the distant signal and one in a non-receptive position, in which the experimental E.M.F. is inserted. The same detector system is then shifted over by a switch from one to the other

But precautions are necessary, since the effect of atmospherics is not the same in both frames. Very great care is necessary to shield the artificial valve generator, which is used to create the applied E.M.F. in the frame to imitate the E.M.F. due to the signal wave. For further details it will be necessary for the reader to consult special treatises on wireless telegraphy.

In conclusion, a few general remarks may perhaps be permitted as to the relation of scientific research to technical and especially electrical engineering progress.

One of the most important of the deductions which may be made from past experience is the very obvious one that we cannot foresee what fields, opened in a spirit of

pure scientific enquiry, will come to be fruitful in technic a applications. Such purely scientific and highly mathematical investigations as those of Maxwell, in establishing the equations of the electromagnetic field, paved the way for Hertz's experimental researches, and these led us finally to radio-communication by electromagnetic waves. Crookes' investigations on electric discharge in high vacua gave birth to the further researches which opened to us the field of X-radiation and to the manufacture of the carbon-filament electric lamp. Phenomena connected with the blackening of incandescent electric lamps and the discharge of negatively electrified particles from the carbon filament resulted in the invention by me of the rectifying thermionic valve, in 1904, and this again to the evolution of the three-electrode valve by others, with all its astounding powers of amplification and generation of oscillations, and this, ultimately, gave us the present-day wonders and pleasures of broadcasting. Hence we see that in the great research laboratories of far-seeing United States Electric Corporations, and also, to some extent here in Great Britain, in such important Research Laboratories as that of the General Electric Company at Wembley, England (see *Frontispiece*), no attempt is or should be made to pin down competent original investigators to work which will be of immediate practical use. What is requisite is some new knowledge or discoveries in physical and chemical science, and we may have full faith that the applications will follow in due course.

In the next place we may note that important scientific discoveries are in many cases the result of a sort of happy accident or unlooked for effect, but such chances only fructify in the hands of very observant and painstaking scientific workers who can take advantage of them. The apparently trivial observation that there was ½ per cent. difference between the density of nitrogen obtained from the air and that from chemical sources led the late Lord Rayleigh to the discovery of Argon, and then Ramsay followed with the discovery of four more inert gases in the

atmosphere, and opened up an entirely new chapter in chemical science. The stray observation of Becquerel that photographic plates placed in paper envelopes were blackened by uranium salts laid outside the envelope, even if the uranium had not been exposed to daylight, led to the epoch-making discovery of radio-active substances by M. and Mde. Curie and their associates.

It is of great importance, therefore, to train in engineering students the powers of observation and careful persistent experimentation. In the case of young investigators this is best done by associating them for a time with older and more experienced workers in joint researches until the younger man learns to run alone. Our present examination system is the deadly foe of this important mental development.

Furthermore, as many of the problems which invite enquiry lie on the borderland of two or three sciences, these are best dealt with by carefully organised team work, in which specially trained workers in the respective sciences have a share and co-operate and, in any case, call for a scientific education not framed too much on specialist lines.

Lastly, as the fruitful fields of enquiry became more and more difficult to find and the possible attainable results less easy to reach, we must make up our minds that valuable positive gains will be set in a matrix of very extensive failures or negative results in the matter of pure scientific research. This implies that very often the end desired can only be reached by a sufficient expenditure of money. Scientific research at present is to some extent like commercial advertising, in that it is not remunerative if conducted on a very small scale or with niggardly outlay. It must be conducted with adequate financial resources if it is to yield any results worth having. Nevertheless, the most splendidly equipped laboratories or the most highly organised plans of campaign will fail to give us truly great results unless those who are in control have that spark of divinity we call genius for scientific investigation. It

is not the material resources or instrumental appliances which have made the laboratories of the Royal Institution of Great Britain the birthplace of some of the greatest discoveries made by the intellect of man. It was due to the incommunicable and intuitive insight into the secret processes and phenomena of nature possessed by the men who worked there—to the supreme abilities of Davy, Faraday, Tyndall, Frankland, and Dewar, as experimental investigators.

The genius of such men cannot be produced at will. It can only be cherished as a national possession when found. Let us see to it, then, that such genius, whenever found, shall be given adequate opportunity for labours which, even if they seem entirely destitute of practical value at the moment, will certainly yield their fruit at some future time in divers and very unexpected ways.

We have, however, made great progress since 1910 in the organisation of pure and applied scientific research, especially under the guidance of the Committee of the Privy Council for Scientific and Industrial Research, and the progress made can best be judged by a perusal of the Report of that Committee for the year 1925–26 which was published as a Report to Parliament in 1927. To it the reader desirous of more information may be referred. It contains an admirable statement of the widespread operations of this Committee.

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